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Monomethlhydrazine Propellant/Material Compatibility Investigation and Results

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The work reported herein was sponsored by the Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, California, under Military Interdepartmental Purchase Request, Project Order Number F04611-77-X-0002, JON 305810QI. The program was administered under the Technical Direction of 1st Lt W. T. Leyden (AFRPL/LKDP).

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The compatibility effect of monomethylhydrazine propellant on aluminum and corrosion-resistant steel materials in the welded form was investigated. Storage tests were conducted using specification grade MMH and a special grade (doped with water and carbon dioxide) for a period 123 days at a temperature of 71.1°C (160°F).
Based upon the experimental test results, it was concluded that (1) aluminum alloy types 5052, 5086, 6061, and CRES types 316, 316L, 321, and 430 are → over

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20. ABSTRACT (Cont'd)

compatible with both grades of MMH, and (2) that these materials and similar generic types would be suitable materials for use as shipping and storage containers for MMH propellant.

CONTENTS

TABLES

FIGURES

I. INTRODUCTION

A. Discussion

Propellant/material compatibility data are needed for alternate structural alloys suitable for shipping and storage containers for monomethyl-hydrazine (MMH) propellant (Tables 1, 2) (Refs. 1, 2). At the present time the Department of Transportation (DOT) has authorized only corrosion-resistant steel (CRES) types 304 and 347 for tanks and drums for MMH service (Ref. 3 and 4). The capacity of available shipping equipment and storage facilities will be taxed based upon the MMH propellant ready supply and usage requirements forecast for the NASA Space Shuttle Program.

Different materials such as aluminum alloys and other CRES types were investigated for use on these applications by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology (Caltech) for the U.S. Air Force. Alloy types considered to be candidate materials for construction were selected from the DOT regulations (Ref. 3, Sect. 179), and include:

(1) Aluminum alloys
Types 5052, 5083, 5086, 5154, 5254, 5454, 5652, and 6061.

(2) Corrosion-resistant steel alloys
Types 316, 316L, and 430.

B. Objective

The objective of this program is to demonstrate the compatibility of MMH propellant with several specified alloys that meet the requirements of DOT shipping specifications.

C. Scope

The overall program consists of three phases:

Phase 1 - compatibility data compilation
Phase 2 - compatibility determinations
Phase 3 - documentation (final report)

Phase 1 has been completed, and the literature search details and results have been published (Ref. 5).

The scope of work presented in this report covers phases 2 and 3, i.e., the compatibility determinations and documentation (final report).

II. COMPATIBILITY INVESTIGATIONS

The literature search (Ref. 5) revealed a lack of material compatibility information for MMH and the materials of interest. Based upon the recommendation in Reference 5, Phase 2 was implemented.

An experimental and analytical program was conducted to investigate the effects of monomethylhydrazine (MMH) real-time exposure on selected materials, and to determine the compatibilities.

JPL standards, procedures, methods of analyses, equipment, and facilities were utilized. For information purposes, these were developed under the ongoing JPL long term (10-year) storage testing program (sponsored by NASA[1] since 1962) with earth-storable propellants[2] and different materials used for spacecraft chemical propulsion systems (Ref. 6).

A. Program Requirements

1. Propellant Grades

The MMH propellant grades were limited to the specification (baseline) and contaminated (doped) grades, Table 3. The combination for the contaminated (doped) grade was established for this program, and was considered to be the worst case relative to "end use or service conditions".

2. Material Types

The specific aluminum and CRES alloy types considered for this program are indicated in Table 4. The chemical compositions and mechanical properties are listed in Tables 5 and 6, and these are in accordance with the American Society for Testing and Materials, Specifications ASTM B209-74 (Ref. 7) and ASTM A240-75a (Ref. 8).

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[1] NASA - Office of Aeronautics and Space Technology (NASA-OAST) and NASA - Office of Space Sciences (NASA-OSS).

[2] Propellants: fuels, amine types; oxidizer, nitrogen tetroxide.

3. Environmental Conditions

The requirements established for the experimental storage test were as follows:

120 days exposure at 71.1°C (160°F)

B. Experimental Test Program

A comprehensive experimental test program was designed to meet the objectives and comply with the requirements. The test units are indicated in Table 7, which identifies propellant grades, material types, and number of test units.

The key features include:

(1) A baseline program for determining the compatibility of materials using a representative number of materials and propellant combinations

(2) Testing generic types of aluminum alloys in lieu of testing every type.

Pertinent details covering the above follows.

C. Test Propellant

Specification grade MMH propellant was used as the baseline. This conformed with MIL-P-27404A requirements, Tables 1 and 3, and Reference 1. The batch was drawn from the lot used on the NASA Mariner Mars flight project, Viking Orbiter 1975.

The doped MMH was made from the above and conformed with the requirements of Table 3.

Assays of the propellant grades are presented in Table 8.

D. Test Specimen Details

1. Configuration

The rectangular specimen configuration is defined in Figure 1 and Reference 9. This geometry is the same as the standard welded type form used in the JPL material compatibility program (Ref. 6) except for deviations of thickness and surface finish as follows:

(1) Thickness — increased from 0.076 cm (0.030 in.) to 0.16 cm (0.063 in.).

(2) Surface finishes — changed from a "grind finish" (0.4 μm, 16 μin. max.) to surfaces left in the "as received conditions," and edges "as milled" conditions (1.6 μm, 63 μin. max.).

2. Test Materials

The specific materials used in this test program (Table 7 and Ref. 9) include:

(1) Aluminum alloy — sheet stock types 5052H34, 5086H32, 5456H323, and 6061T6.

(2) Corrosion-resistant steel alloy — sheet stock types 316, 316L, 321, and 430; annealed condition.

Certifications for the raw materials indicate compliance with the ASTM chemical composition and mechanical properties specifications, Tables 5 and 6, and References 7 and 8.

3. Preparation

All test specimens were prepared by JPL except for the welding operation. Each material type was machined as a group (Fig. 1), parts serialized upon completion, and cleaned (Ref. 10) prior to welding. It is noted that the cleaning requirements used on this program were the same as the ultrahigh standards (Ref. 10) used by JPL on chemical propulsion systems for unmanned planetary spacecraft. An important detail of the procedure involves the cleaning solvent; only isopropyl alcohol (IPA) was used on all items (hardware, glassware, etc.) for this program.

The test specimens were fusion welded using the gas tungsten arc process with the filler metals listed in Table 9 and Reference 11.

The work was accomplished by an industrial organization[3] specializing in rail tank car manufacturing and repair (that comply with DOT and AAR[4] standards), and produced weldments representative for that field of industry. This practical aspect directly supports the objective of the program (IB).

The weld joints were inspected optically under low magnification (10×) and radiographically (X-ray). There was evidence of porosity in the aluminum samples, types 5052 and 6061. However, all weldments and specimens were considered acceptable for both quality and other accumulated effects (for example, penetration, melt-through, undercutting, etc.) resulting from the welding. There were no postweld thermal treatments or weld cleanup operations performed.

The parts were completed by machining to the final length (Fig. 1).

4. Pretest Cleaning

The final cleaning operation (Ref. 10) was performed on all specimens in the "as welded condition," and parts sealed in nylon bags.

E. Test Unit Configuration (Specimen/Capsule)

The test specimen/propellant/capsule combination used for storage testing is shown in Figures 2 and 3. This glass ampule or test container design and method of testing is the same as that developed under the JPL program (Ref. 6). The upper portion was fused to provide a hermetic seal and completely isolate tne test item and MMH propellant from the external environment.

F. Storage Testing

The storage testing was performed in the material compatibility facilities located at the JPL Edwards Test Station, Edwards, California (Ref. 6).

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[3]Railgard Inc., Daggett, California.

[4]American Association of Railroads.

All test units (Table 7) were subjected to the required storage test at high temperature. These units were tested as a group in a special oven (JPL equipment). After stabilization, the ambient temperature was continuously maintained at $71.1 \pm 1.1^{o}C$ ($160 \pm 2^{o}F$) for a duration of 123 days.

The exposure test was monitored for compliance and safety at weekly intervals throughout the program. The test requirements were met with no deviations.

After completing the 123 days exposure, the storage test was concluded. The sealed test units were returned to JPL-Pasadena in a frozen condition ready for posttest analyses.

III. POSTTEST ANALYSIS PROCEDURE

A. Discussion

1. Standard Procedure

The planned posttest analysis procedure is outlined in Figure 4. It provides for measurements of capsule pressure due to presence of decomposition gases from MMH, an analysis of the propellant, and the determination of dissolved metals in the propellant due to corrosion of metal test specimens. Visual inspections of the propellant and specimens are also made during the procedure.

None of the capsules initially examined by the standard posttest analysis procedure had enough internal pressure to register on the Bourdon-type pressure gauge; therefore an alternate procedure was devised that gives a more sensitive indication of the amount of decomposition gases than can be measured with the pressure gauge.

2. Alternate Procedure

The alternate posttest procedure (see Figure 5), was applied to half the test capsules (baseline propellant and one doped propellant for each alloy type) and all six of the control capsules (propellant only).

The basic difference between the standard and alternate procedure is that in the latter the noncondensible decomposition gases are pumped out and separated from the frozen propellant and analyzed separately. As little as a fraction of a cubic centimeter of decomposition gases can be collected, measured, and analyzed.

B. Decomposition Gases

1. Composition

The exact stoichiometry of the decomposition of MMH under the test conditions employed is unknown. Previous studies (Ref. 5) show that the principal decomposition products are probably ammonia, monomethylamine, azomethane, nitrogen, and methane. Other unidentified species and hydrogen have been detected in trace amounts. In the alternate analysis procedure, only the noncondensible gases nitrogen, methane, and hydrogen (if present), are measured and analyzed. The nonvolatile (at LN_2 temperature) products of decomposition (ammonia, monomethylamine, and azomethane) will remain in the propellant. The analysis procedure used in this investigation only provides for a quantitative analysis for ammonia in the propellant. Although a trace amount of an unidentified constituent (probably monomethylamine) was found in some of the propellant analyses, no quantitative results are reported because of difficulty of identitying and measuring such small concentrations with the analytical procedures used.

2. Capsule Pressure

The mean volume of the test capsules is 82 $\pm$ 1 cm^3. With 20 cm^3 of propellant, the ullage volume of the capsule can be assumed to be 62 $\pm$ 1 cm^3, neglecting the small volume of the test specimen. The total internal volume of the breaker fixture is approximately 305 cm^3. When the tip of the capsule is broken in the evacuated breaker fixture, and decomposition gases on the capsule expanded into the internal volume of the system, the pressure is measured with the gauge on the breaker fixture. Allowing for the expansion ratio, any capsule pressure greater than 3.5 N/cm^2 (5 psia) should be readily measureable. None of the capsules tested indicated any pressure greater than the autogenous vapor pressure of MMH (0.6 N/cm^2, 0.8 psia at room temperature).

3. Calculated Capsule Pressure

For the specimens analyzed by the alternate procedure, the pressure due to the total measured volume of the noncondensible gases can be calculated from the perfect gas law. In addition to the pressure due to the noncondensible gases, there will be a small contribution from the other condensible decomposition products, principally ammonia, monomethylamine, and azomethane. Data are available for computing the pressure contribution from ammonia; however, the contribution from the other minor condensible constituents cannot be readily estimated. Even if the ammonia and other nonvolatile decomposition products exceed 75 mole percent of the total decomposition products, their combined contribution to capsule pressure should not exceed 20 percent of the total. A discussion of the calculation of capsule pressure and contributions of the various decomposition products has been presented elsewhere (Ref. 6).

4. Percentage MMH Decomposed

The percentage of MMH decomposed can be calculated from the total weight of the products of decomposition. However, as pointed out earlier, the exact stoichiometry of the decomposition reaction is unknown, and the analytical procedure does not allow for the unequivocal determination of all the possible products. The determination of the percentage of propellant decomposed must be considered, at best, only an approximation.

C. Propellant Analysis

1. Impurities

The NH_3, H_2O, and UDMH contents of the propellant samples are analyzed by gas chromatography using a 0.64-cm-diameter x 2-m-long (1/4-in.-diameter by 6-ft.-long) column containing powdered Teflon coated with 15% by weight triethanolamine. Helium carrier gas is used at a flow rate of 100 cm^3/min and a column temperature of 90°C. The column separates NH_3, UDMH, H_2O, and MMH in that order.

2. Metals

The MMH removed from the capsule is combined with water rinsings from the capsule and specimen and diluted to 50 cm^3 with distilled water. Analysis for appropriate metal ions (Al for aluminum alloys, and Fe, Cr, and Ni for CRES alloys) is made by atomic absorption using a Perkin-Elmer model 303 Atomic Absorption Spectrophotometer equipped with a model HGA-2100 graphite furnace. The use of the HGA furnace offers sensitivities and detection limits 100 to 1000 times better than flame ionization for most metals. Its use is essential to determine the low levels of metals present in the samples of this investigation.

IV. POSTTEST ANALYSIS PROCEDURE FOR SPECIMENS

The posttest analysis procedure is outlined in Figure 6. Each specimen is examined to determine if physical or metallurgical changes have taken place. Surface conditions are examined at low magnifications with a microscope. Selected surface areas are examined at higher magnifications with a scanning electron microscope (SEM), Fig. 7. A sequence of photo magnifications (e.g. 6CX, 300X, 600X, and 3000X) are taken at the critical locations to reveal dimensional changes and surface topography changes. Specific items include:

(1) Surface finish.
(2) Appearance liquid immersed area (L).
(3) Appearance vapor exposed area (V).
(4) Appearance and location of the liquid/vapor (L/V) interface boundary (Note: specimen wetted area to propellant volume ratio s/v is 0.65 cm^{-1}, Fig. 2).
(5) Presence and distribution of formations, colored stain, or film.
(6) Presence of streaks, mottling, and spotting of surface.
(7) Extent of corrosion or etching; general or local.
(8) Extent of pitting; size, distribution.
(9) Extent of cracking; size, distribution.

The posttest samples are then compared with similar reference (control) samples to determine effects of the test.

V. POSTTEST ANALYSES AND RESULTS

Each specimen was examined visually and microscopically at low magnifications to check for gross manifestations of corrosion. Selected areas were examined at high magnification with a scanning electron microscope. Each specimen was weighed before and after testing to within ±0.1 mg to determine any mass changes due to solution of the metal or build-up of corrosion films.

The test samples in the pretest condition and posttest condition are displayed in photographs, Figures 8 to 15 for aluminum alloys, and Figures 16 to 23 for CRES alloys.

A. Aluminum Alloys: 5052, 5086, 5456, and 6061.

There was no detectable incompatibility of any of the aluminum alloys with either the baseline or doped MMH for the test conditions described. Reference to Tables A-1 and A-2 shows that the volume of decomposition gases (N_2 and CH_4) was the same for all specimens tested and for the control capsules (3491, 3493, 3495, 3591, 3593, and 3595). Contamination of the baseline MMH (500 ppm CO_2 and 3% H_2O) had no measureable effect on decomposition in the presence of the aluminum alloys tested.

None of the aluminum specimens tested in the baseline MMH had any visible tarnish or corrosion. A few of the specimens tested in doped MMH had faint blue, gray, or yellow tarnish films, probably oxide interference films; however, the corrosion was judged to be superficial at most. Weight changes were limited to a few tenths of a milligram, except for two specimens which had evidence of oxide inclusions.

All of the MMH propellant samples in contact with aluminum specimens indicated a build-up of aluminum. Although the concentration was quite variable, most results were in the 10- to 20-μg range for the amount of aluminum dissolved. The baseline pretest aluminum content for the same volume of MMH is about 2 μg. There was no definite indication that the doped propellant caused greater dissolution of aluminum.

B. CRES Alloys: 316, 316L, 321, 430

There was a small but measureable effect of the CRES alloys on the decomposition rate of MMH. Reference to Tables A-1 and A-2 reveals that the 316 and 316L specimens cause approximately double the generation of noncondensible gases (N_2 and CH_4) for the baseline propellant compared to the control MMH capsules. The doped propellants generate about four times as much decomposition gases for 316 and 316L specimens. The effects described above were much smaller for 321 CRES (Mo-free), and apparently absent for 430 CRES (Ni-free). In the worst case, however, the decomposition was very small (calculated 0.035% of the MMH), and well within acceptable limits.

None of the CRES specimens had any visible tarnish caused by exposure to the MMH during test, but most retained localized tarnish due to the welding operations. In all cases there was no evidence of any change in appearance of the specimens. Most of the propellant samples had a faint yellow color, which indicates a build-up of iron concentration.

The CRES specimens all indicated either a negligible weight change or a small weight loss of a few tenths of a milligram. All propellant samples in contact with CRES specimens indicated a small build-up of metallic ion concentrations amounting to about 20 to 180 μg total Fe, Cr, and Ni. The initial baseline content of Fe, Cr, and Ni amounted to 8 μg in 20 cm^3 of MMH.

In all cases, the amount of corrosion, as determined by the total Fe, Cr, and Ni in solution, was appreciably greater for the doped MMH, proving that the higher concentrations of CO_2 and H_2O have a measureable effect on corrosion of CRES alloys. The amount of dissolution of the CRES alloys averaged about 3 or 4 times greater for the doped MMH when compared with the baseline, except for 321 CRES where the difference between the baseline and doped MMH was less. The values (Table A-2) for baseline MMH and doped (mean) MMH are: 17.5, 79; 30, 111; 81, 128; and 30, 115.

C. Scanning Electron Microscopy

All reference (control) and posttest specimens were examined with the scanning electron microscope (SEM) at the critical locations indicated in Fig. 7 at magnifications of 60X, 300X, 600X, and 3000X.

However, only SEM micrographs of the specimen metal surface/weld bead area along the liquid vapor (L/V) interface are shown in Appendices B and C.

None of the SEM micrographs of the posttest specimens indicate any surface changes (such as corrosion or pitting) or other material problems.

VI. MATERIAL RATINGS

A commonly accepted standard corrosion rate of 0.005 cm/year (0.002 in./year) has been assumed as a means for comparing results and determining a compatibility rating.

The posttest results are summarized in Tables A-1 and A-2. In all cases, the total amount of metal dissolved is well below the acceptable limits of corrosion. Hence, these materials would have a high compatibility rating when used with monomethylhydrazine propellant, specification grade per MIL-P-27404A, Ref. 1.

VII. CONCLUSIONS

The compatibility effect of specification grade and contaminated grade (Table 3) MMH has been investigated with different aluminum and corrosion-resistant steel alloys (Table 7) in the welded form. Based upon these experimental results, the conclusions are:

(1) Aluminum alloy types 5052, 5086, 5456, 6061, and CRES types 316, 316L, 321, 430 exhibit a very high degree of compatibility with both grades of MMH at a temperature of 71.1°C (160°F).

(2) The corrosion rates were insignificant.

(3) The aluminum alloy types 5083, 5154, 5254, 5454, and 5652 are considered compatible materials on the basis of similarity and comparison.

(4) The materials investigated are considered suitable for the intended application, IA, and shipping containers.

VIII. RECOMMENDATION

The other elements that make up the total system, such as valves, plumbing, seals, etc., be investigated for suitability relative to material compatibility aspects, design, and performance.

DEFINITION OF TERMS

AAR	American Association of Railroads
AFRPL	Air Force Rocket Propulsion Laboratory (United States)
Al	aluminum
ASTM	American Society for Testing and Materials
CRES	corrosion-resistant steel
DOT	Department of Transportation
JPL	Jet Propulsion Laboratory (California Institute of Technology)
MMH	monomethylhydrazine or methylhydrazine
NASA	National Aeronautics and Space Administration
ppm	parts per million
UDMH	unsymmetrical dimethylhydrazine or uns-dimethylhydrazine

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11. "Process Specification, Welding, Metal and Tungsten Arc Fusion, Detail Specification For," JPL Specification FS505152, Revision B (JPL internal document).

Table 1. Chemical and Physical Properties of Monomethylhydrazine Propellant

Constituent or Property	MIL-P-27404A Amendment 2 Specification Limits
Monomethylhydrazine ($N_2H_3CH_3$) assay, % by weight	98.3 min
Water, % by weight	1.5 max
Particulate, mg/l	10.0 max
Density, g/ml at 25°C (77°F)	0.870 to 0.874

Table 2. Summary of Properties of Monomethylhydrazine Propellant

Chemical name: methylhydrazine

Chemical formula: $CH_3N_2H_3$

Formula weight: 46.0724

Property	Value
Freezing point	-52.37°C
Boiling point	87.65°C
Critical temperature	312°C
Critical pressure	81.3 atms
Critical density	0.29 g/cc
Density, liquid	0.8702 g/cc
Vapor pressure, 25°C	49.47 mm Hg
Surface tension, 25°C	33.83 dyne/cm
Viscosity, liquid, 25°C	0.775 cp
Heat of fusion	2.490 kcal/mole
Heat of vaporization, 25°C	9.648 kcal/mole
Heat capacity, liquid, 25°C	32.25 cal/mole-°C
Heat capacity, gas, 25°C	17.0 cal/mole-°C
Heat of formation, liquid, 25°C	13.106 kcal/mole
Heat of combustion, liquid	311.7 kcal/mole
Entropy, liquid, 25°C	39.66 cal/mole-K
Entropy, ideal gas, 25°C	72.02 cal/mole-K
Flash point	1.1°C

Table 3. Monomethylhydrazine Propellant Requirements

Item	Constituent Property, or Condition
Propellant	Baseline — Specification grade MMH, Table 1
Contamination	Doped —
Carbon dioxide (CO_2)	500-550 parts per million (ppm)
Water (H_2O)	3% by weight (replaces 1.5%, Table 1)

Table 4. Materials Considered for Compatibility Studies

Material	Types: Available in Small Lot Quantities	Types: Either Obsolete or Only Available in "Mill Run Lots"
Aluminum alloys	5052 5086 5456[a] 6061	5083 5154 5254 5454 5652
Corrosion-resistant steel alloys	316, 316L, 321,[b] 430	

[a]Proposed as a substitute for 5454; alloy more commonly used.

[b]Type 321 added.

Table 5. Chemical Composition Limits of Materials[a]

Type Material	Element													Other
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	C	P	S	Ni	
	Aluminum Alloy per ASTM B209-74 (Ref. 7)													
5052	0.45	+Fe	0.10	0.10	2.2-2.8	0.15-0.35	0.10		Balance					0.15
5083	0.40	0.40	0.10	0.40-1.0	4.0-4.9	0.05-0.25	0.25	0.15	Balance					0.15
5086	0.40	0.50	0.10	0.20-0.7	3.5-4.5	0.05-0.25	0.25	0.15	Balance					0.15
5154	0.45	+Fe	0.10	0.10	3.1-3.9	0.15-0.35	0.20	0.20	Balance					0.15
5254	0.45	+Fe	0.05	0.01	3.1-3.9	0.15-0.35	0.20	0.05	Balance					0.15
5454	0.40	+Fe	0.10	0.50-1.0	2.4-3.0	0.05-0.20	0.25	0.20	Balance					0.15
5456	0.40	+Fe	0.10	0.50-1.0	4.7-5.5	0.05-0.20	0.25	0.20	Balance					0.15
5652	0.40	+Fe	0.04	0.01	2.2-2.8	0.15-0.35	0.10		Balance					0.15
6061	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	0.15	Balance					0.15
	Corrosion-Resistant Steel Alloys per ASTM A240-75a (Ref. 8)													
304[b]	1.00	Balance		2.00		18.00-20.00				0.08	0.045	0.030	8.00-10.50	0.10
304L[b]	1.00	Balance		2.00		18.00-20.00				0.03	0.045	0.030	8.00-12.00	0.10
316	1.00	Balance		2.00		16.00-18.00				0.08	0.045	0.030	10.00-14.00	Mo 2.00-3.00
316L	1.00	Balance		2.00		16.00-18.00				0.03	0.045	0.030	10.00-14.00	Mo 2.00-3.00
321	1.00	Balance		2.00		17.00-19.00				0.08	0.045	0.030	9.00-12.00	Ti 5xC min-0.70 max
347[b]	1.00	Balance		2.00		17.00-19.00				0.08	0.045	0.030	9.00-13.00	Cb + Ta 10xC min-1.10 max
430	1.00	Balance		1.00		16.00-18.00				0.12	0.040	0.030	0.75	

[a] Limits are in percent maximum.

[b] Included for information purposes.

Table 6. Mechanical Property Limits of Materials

Material Alloy or Type	Temper[a,b,c]	Thickness,[c] mm	Thickness,[c] (in.)	Tensile Strength, MPa (KSI) Minimum	Tensile Strength, MPa (KSI) Maximum	Yield Strength, MPa (KSI) Minimum	Yield Strength, MPa (KSI) Maximum	Elongation Minimum,[e] %
Aluminum Alloy per ASTM B 209-74 (Ref. 7)								
5052	0	1.29-2.87	(0.051-0.113)	172 (25.0)	214 (31.0)	66 (9.5)	–	19
5052	H34	1.29-2.87	(0.051-0.113)	234 (34.0)	283 (41.0)	179 (26.0)	–	6
5083	0	1.29-38.10	(0.051-1.50)	276 (40.0)	352 (51.0)	124 (18.0)	200 (29.0)	16
5083	H323	1.29-3.18	(0.051-0.125)	310 (45.0)	372 (54.0)	234 (34.0)	303 (44.0)	8
5086	0	1.29-6.32	(0.051-0.249)	241 (35.0)	303 (44.0)	97 (14.0)	–	18
5086	H32	1.29-6.32	(0.051-0.249)	276 (40.0)	324 (47.0)	193 (28.0)	–	8
5154	0	1.29-2.87	(0.051-0.113)	207 (30.0)	283 (41.0)	76 (11.0)	–	16
5154	H32	1.29-6.32	(0.051-0.249)	248 (36.0)	296 (43.0)	179 (26.0)	–	8
5254	0	1.29-2.87	(0.051-0.113)	207 (30.0)	283 (41.0)	76 (11.0)	–	16
5254	H32	1.29-6.32	(0.051-0.249)	248 (36.0)	296 (43.0)	179 (26.0)	–	8
5454	0	1.29-2.87	(0.051-0.113)	214 (31.0)	283 (41.0)	83 (12.0)	–	16
5454	H32	1.29-6.32	(0.051-0.249)	248 (36.0)	303 (44.0)	179 (26.0)	–	8
5456	0	1.29-38.10	(0.051-1.50)	290 (42.0)	365 (53.0)	131 (19.0)	207 (30.0)	16
5456	H323	1.29-3.18	(0.051-0.125)	331 (48.0)	400 (58.0)	248 (36.0)	317 (46.0)	6
5652	0	1.29-2.87	(0.051-0.113)	172 (25.0)	214 (31.0)	66 (9.5)	–	19
5652	H32	1.29-2.87	(0.051-0.113)	214 (31.0)	262 (38.0)	159 (23.0)	–	7
6061	0	0.53-3.25	(0.021-0.128)	–	152 (22.0)	–	83 (12.0)	16
6061	T6	0.53-6.32	(0.021-0.249)	290 (42.0)	–	241 (35.0)	–	10
Corrosion-Resistant Steel Alloys per ASTM A240-75a (Ref. 8)								
304[d]	Annealed	under 4.76	(under 0.188)	515 (75.0)	–	205 (30.0)	–	40
304L[d]				485 (70.0)	–	170 (25.0)	–	40
316				515 (75.0)	–	205 (30.0)	–	40
316L				485 (70.0)	–	170 (25.0)	–	40
321				515 (75.0)	–	205 (30.0)	–	40
347[d]				515 (75.0)	–	205 (30.0)	–	40
430				450 (65.0)	–	205 (30.0)	–	22

[a]Aluminum alloy temper designations: annealed, 0; intermediate, H; solution-treated and precipitation-treated, T.

[b]Aluminum alloy, temper 0 included for comparison purposes and background information relative to "Tank Car" materials and construction. The applicable specification (Ref. 2, par. 179.100-7) states: "For fabrication, the parent metal may be 0, H112, or H32 temper, but design calculations must be based upon minimum tensile strength 0 temper welded condition.

[c]Applicable to Phase 2 test specimen: aluminum alloy temper H and T; sheet stock thickness 1.600 mm (0.063 in.).

[d]Included for information purposes.

[e]Elongation in 50.8 mm (2.0 in.) minimum, %.

Table 7. Experimental Test Units — Materials and Propellants

Material	Type	Number of Test Units		
		Test	Baseline	Reference (Control)
Aluminum alloys	5052H34	3	1	1
	5086H32	3	1	1
	5456H323	3	1	1
	6061T6	3	1	1
Corrosion resistant steel alloys	316 Annealed	3	1	1
	316L Annealed	3	1	1
	321 Annealed	3	1	1
	430 Annealed	3	1	1
Test propellant		Doped MMH	Spec. Grade MMH	None
Number — test specimens and propellant		24	8	8
Number — Reference (control) Propellant only		3	3	—

Table 8. Assays of Monomethylhydrazine

Constituent or Property	Specification MIL-P-27404A	Typical Analysis by Manufacturer[a]	Typical Analysis by JPL[b]	Analysis of Test (AFRPL) Propellant	Analysis of Doped Propellant
Monomethylhydrazine ($N_2H_3CH_3$) Assay, % by weight	98.3 min	98.6 – 99.3	97.1 – 99.2	98.7	96.6
Water, % by weight	1.5 max	0.36 – 1.20	0.47 – 1.95	1.06	3.0
Ammonia, % by weight	Not required	–[c]	0.10 – 0.11	0.14	–
UDMH, % by weight	Not required	–	0.23 – 0.82	0.1	–
Particulates, mg/l	10 max	0.2 – 0.4	–	<0.1	–
Carbon dioxide, % by weight	Not required	–	–	0.0011	0.0525
Density, g/cm^3 at 298 K	0.870 – 0.874	0.870 – 0.872	–	0.873	–
Dissolved metals					
Aluminum, % by weight	Not required	–	–	0.00001	–
Iron, nickel, and cobalt, % by weight	Not required	–	–	0.00004	–
Drum numbers	–	H385 H468 H3203 H3831 H4560 H4784 H4847	H468 H711 H1460 H1509 H2370 H2600 H4829	H468	–

[a]Propellant for NASA flight program – Viking Orbiter 1975. Purchased from and tested by the Olin Corporation under Contract No. F41608-73-D-6308

[b]Propellant for NASA flight programs – Mariner Mars 1971 and Viking Orbiter 1975.

[c]Not measured; data not available.

Table 9. Filler Metals for Gas Tungsten Arc Welding[a]

Material[b]	Specification	Weld Rod Diameter cm	(inch)
Aluminum alloy			
5052H34	QQ-R-566 Class 5356	0.16	(0.063)
5086H32	QQ-R-566 Class 5356	0.16	(0.063)
5456H323	QQ-R-566 Class 5356	0.16	(0.063)
6061T6	QQ-R-566 Class 4043	0.16	(0.063)
CRES			
Type 316	MIL-R-5031 Class 4 (316)	0.16	(0.063)
316L	MIL-R-5031 Class 4 (316)	0.16	(0.063)
321	MIL-R-5031 Class 5 (347)	0.11	(0.045)
430	AWS-A5.9-69 (ER430)	0.11	(0.045)

[a]Material furnished by JPL.

[b]References 9 and 11.

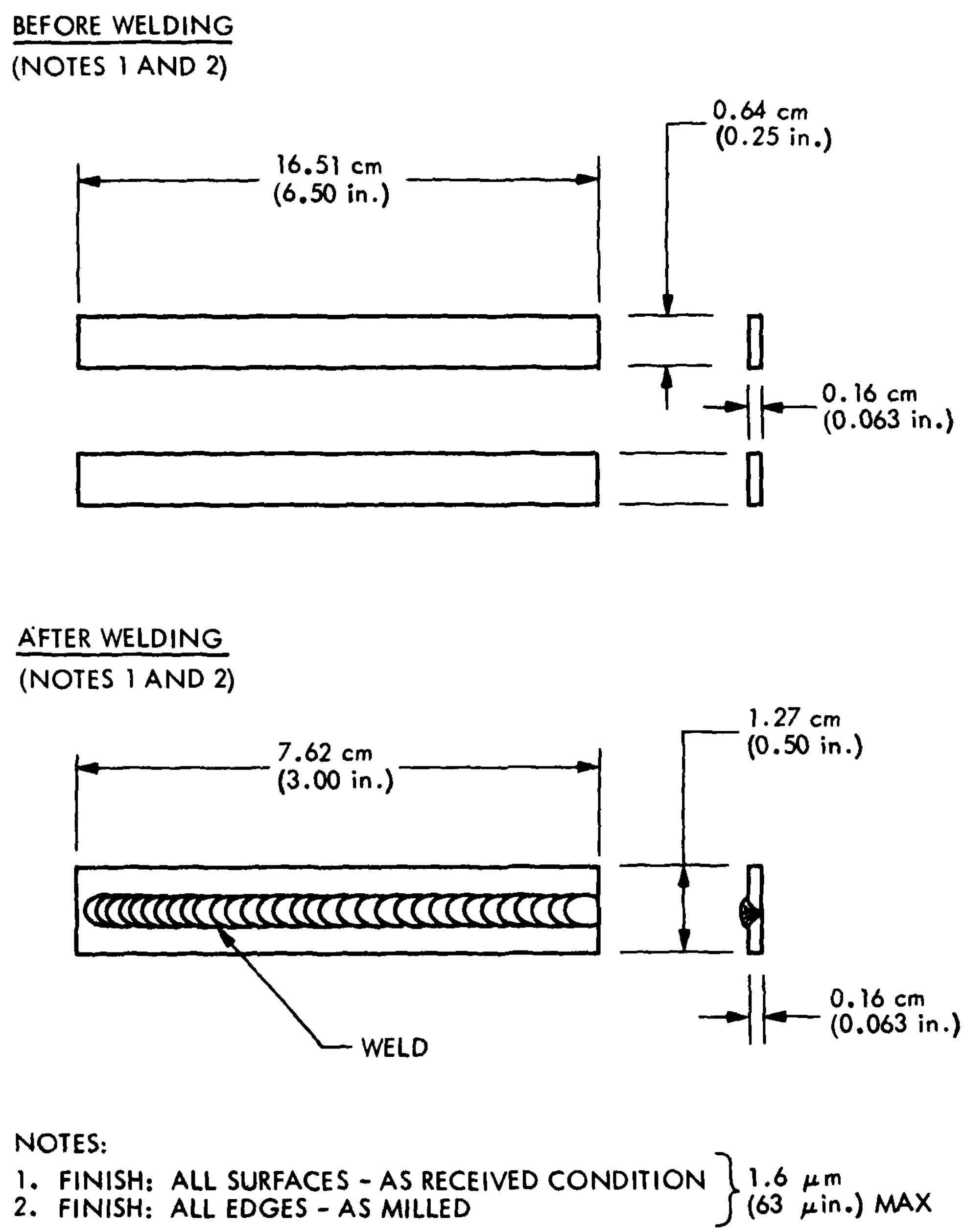

Figure 1. Test Specimen Configuration

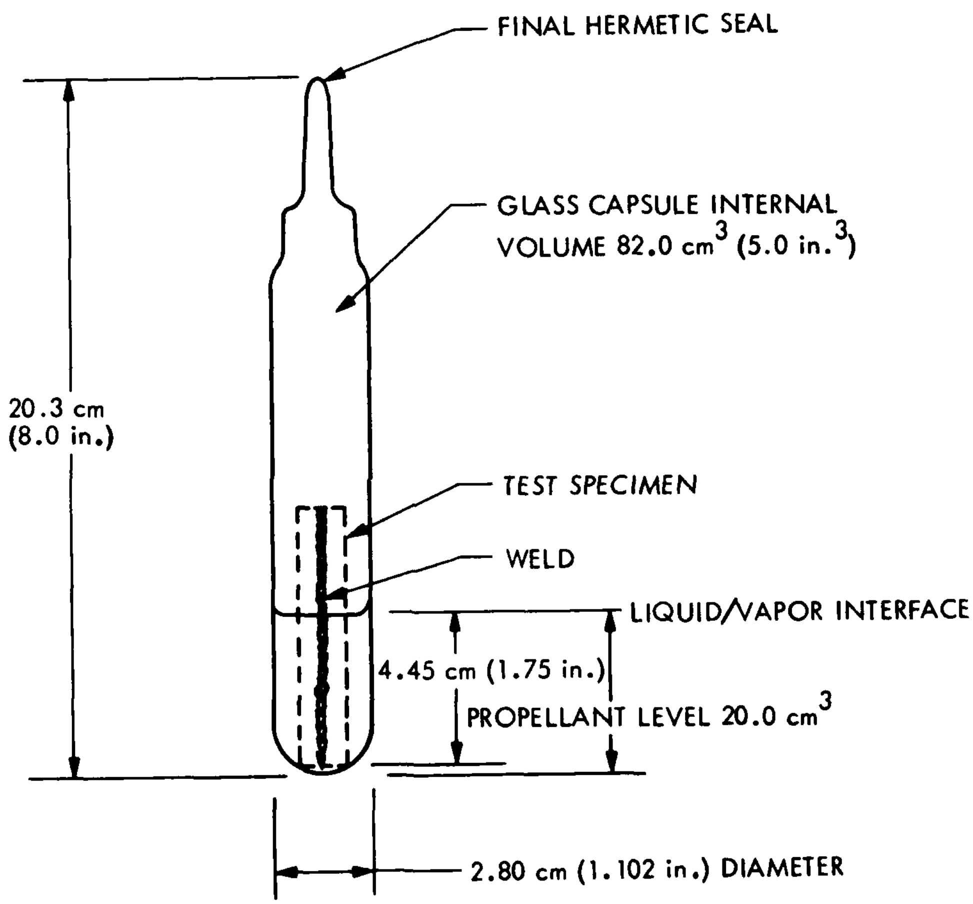

Figure 2. Test Unit Configuration

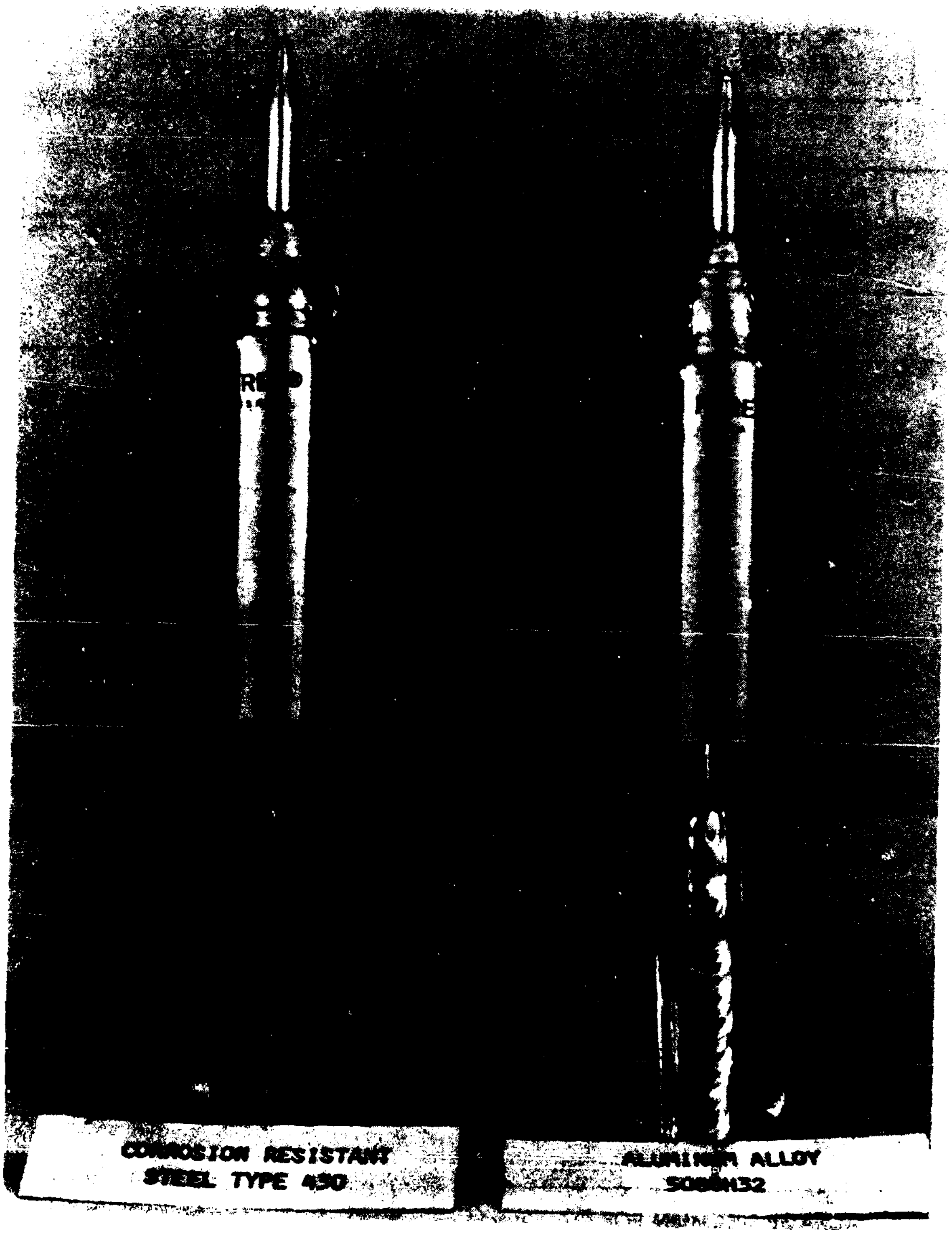

Figure 3. Test Specimen/Capsule

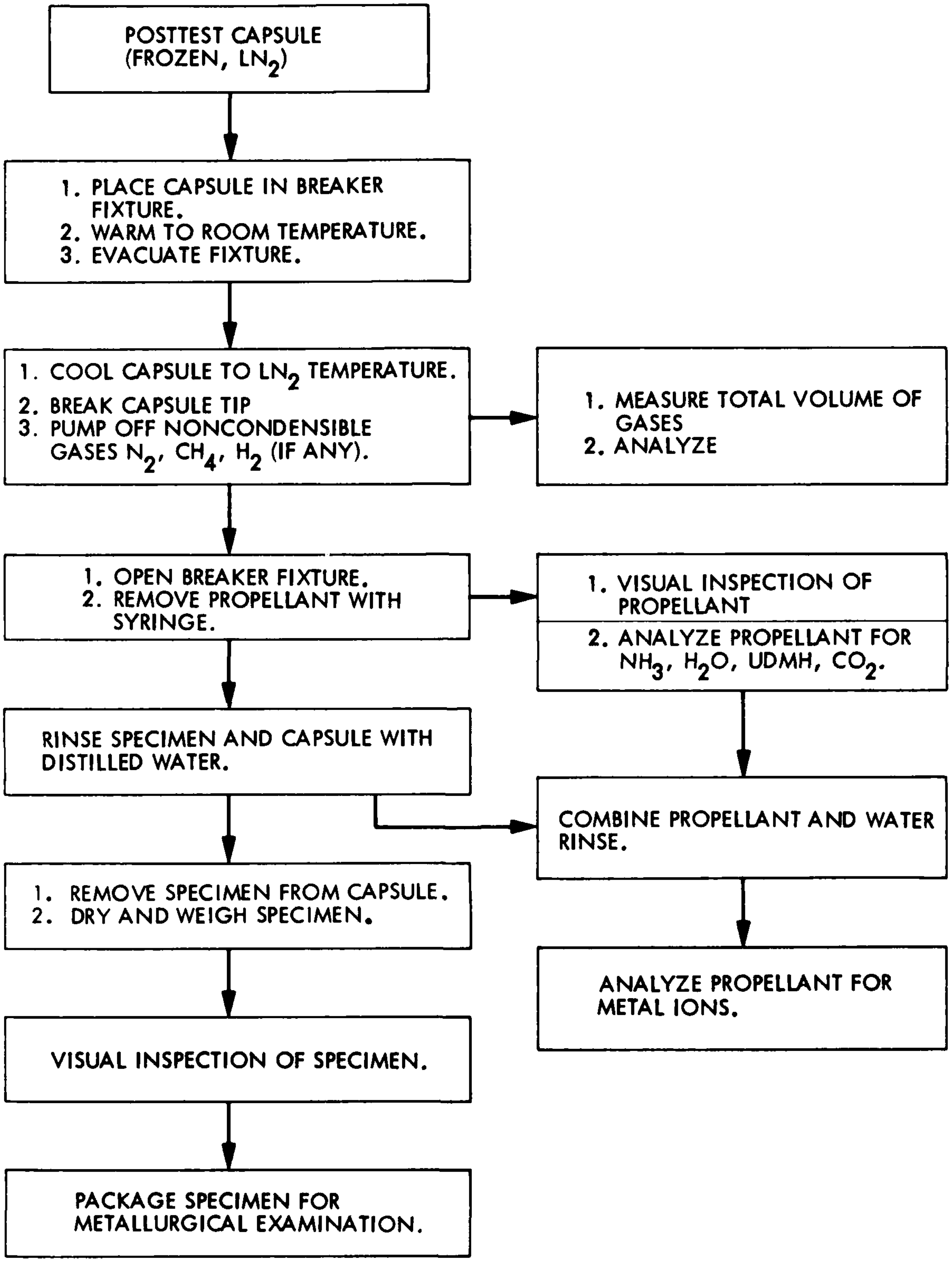

Figure 4. Procedure for Posttest Chemical Analysis

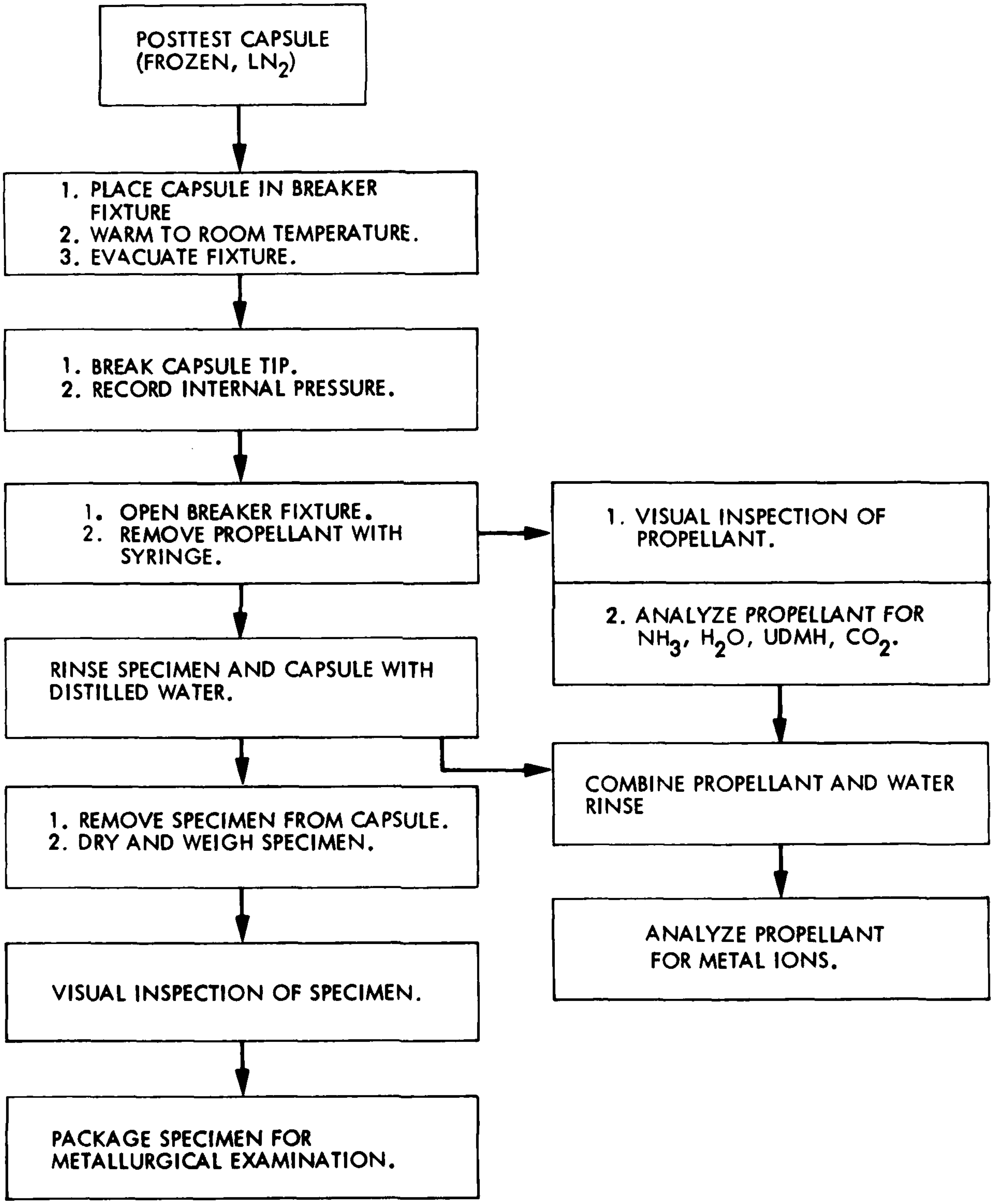

Figure 5. Alternate Procedure for Posttest Chemical Analysis

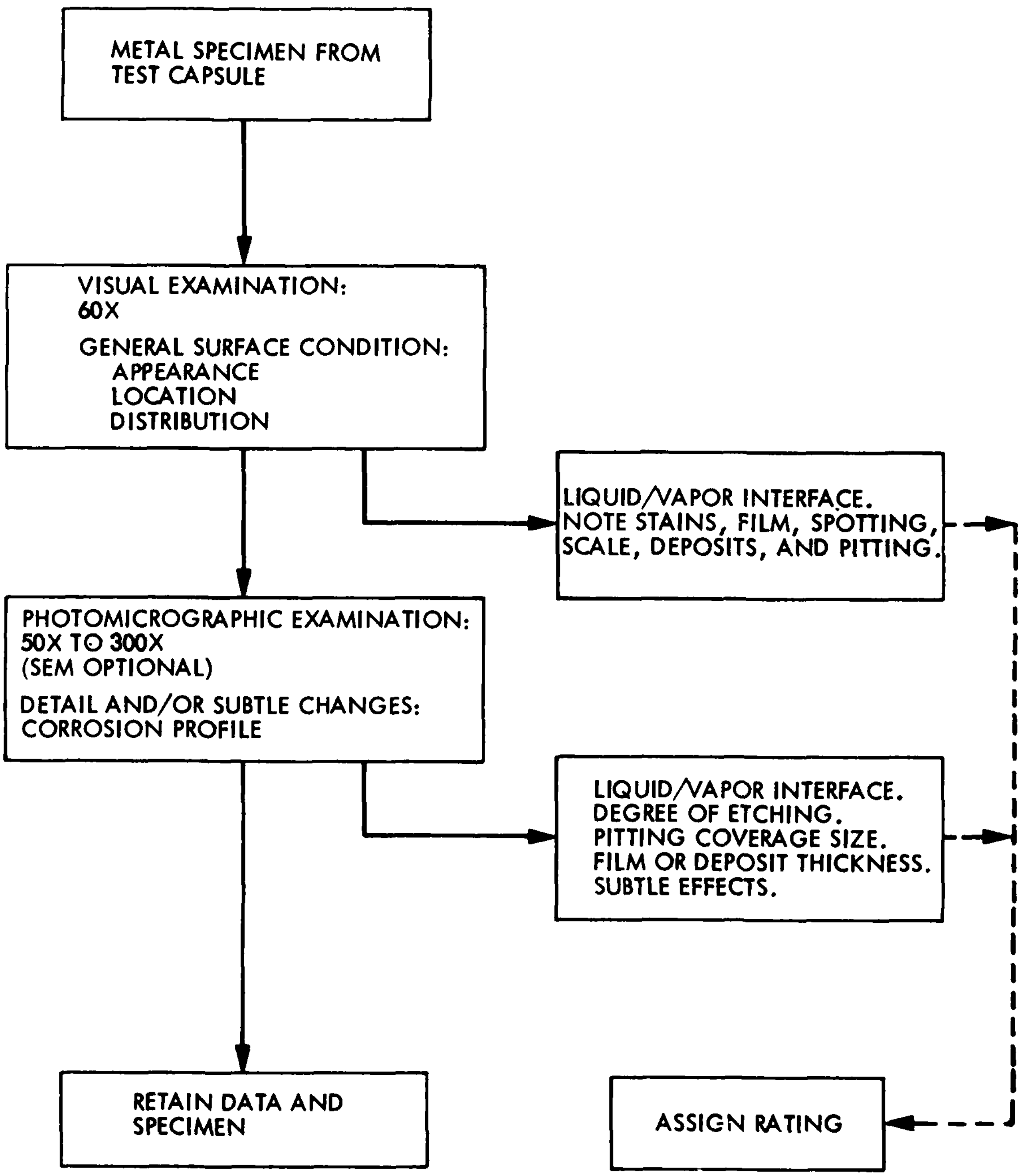

Figure 6. Procedure for Metallic Specimen Analysis

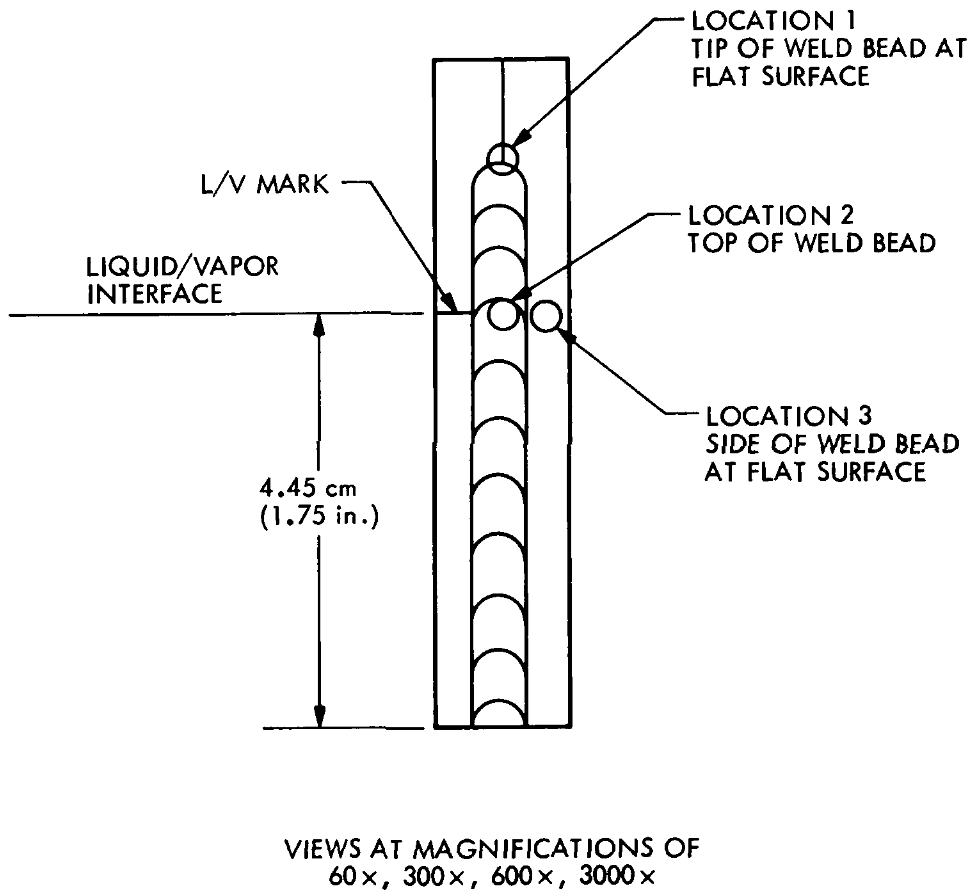

Figure 7. Locations for SEM Photographs

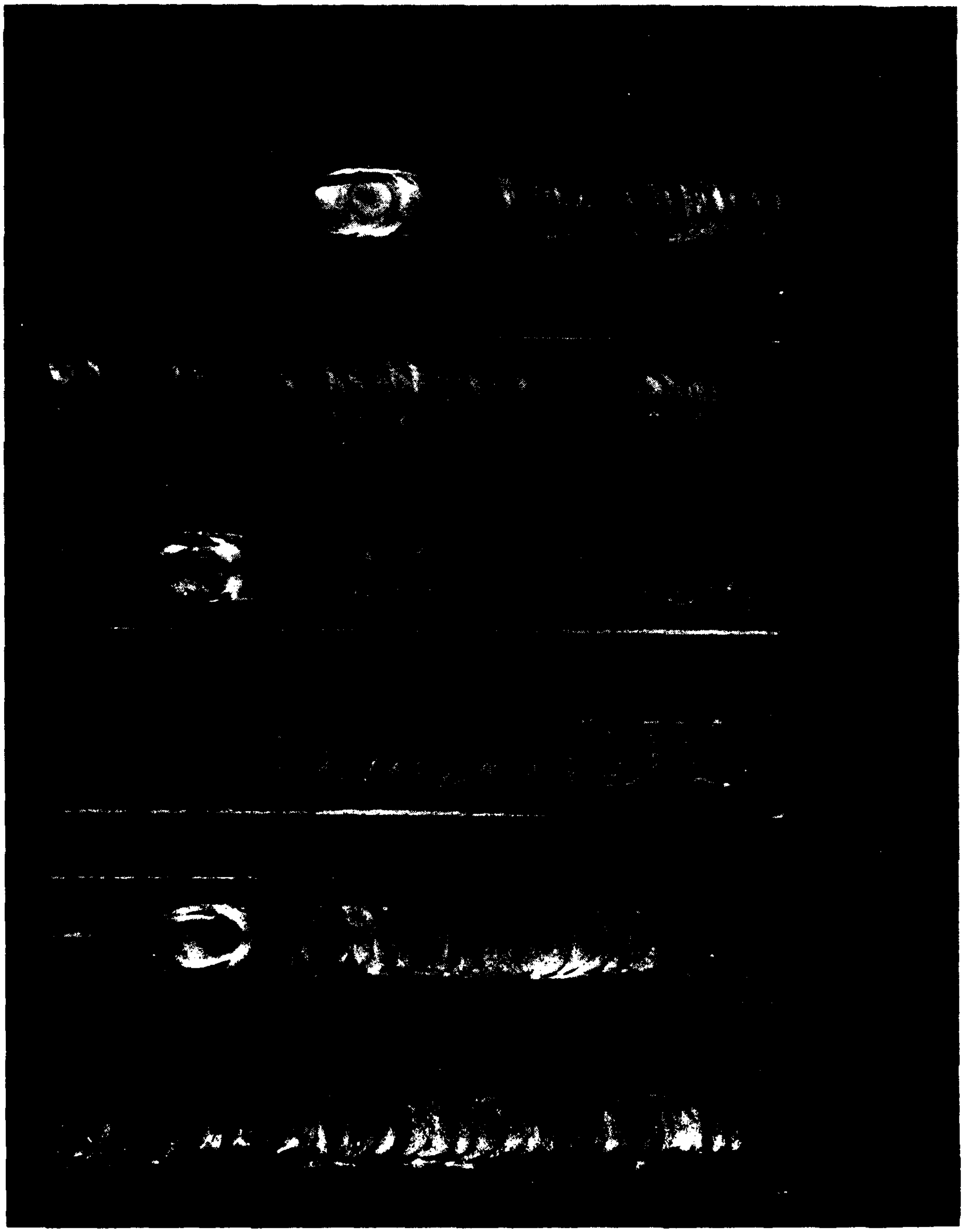

Figure 8. Aluminum Alloy Type 5052 – Snecimens: Pretest

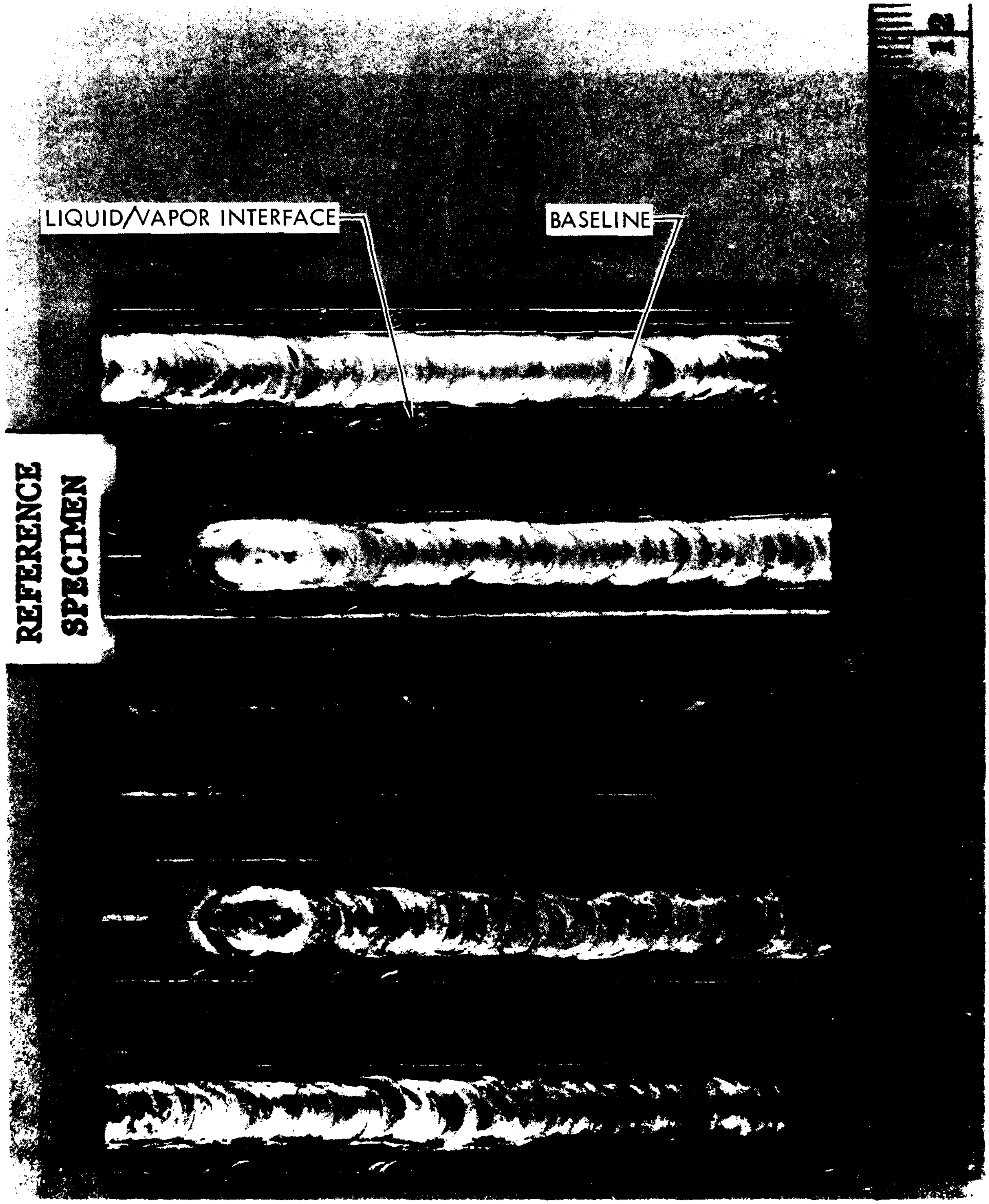

Figure 9. Aluminum Alloy Type 5052 - Specimens: Posttest

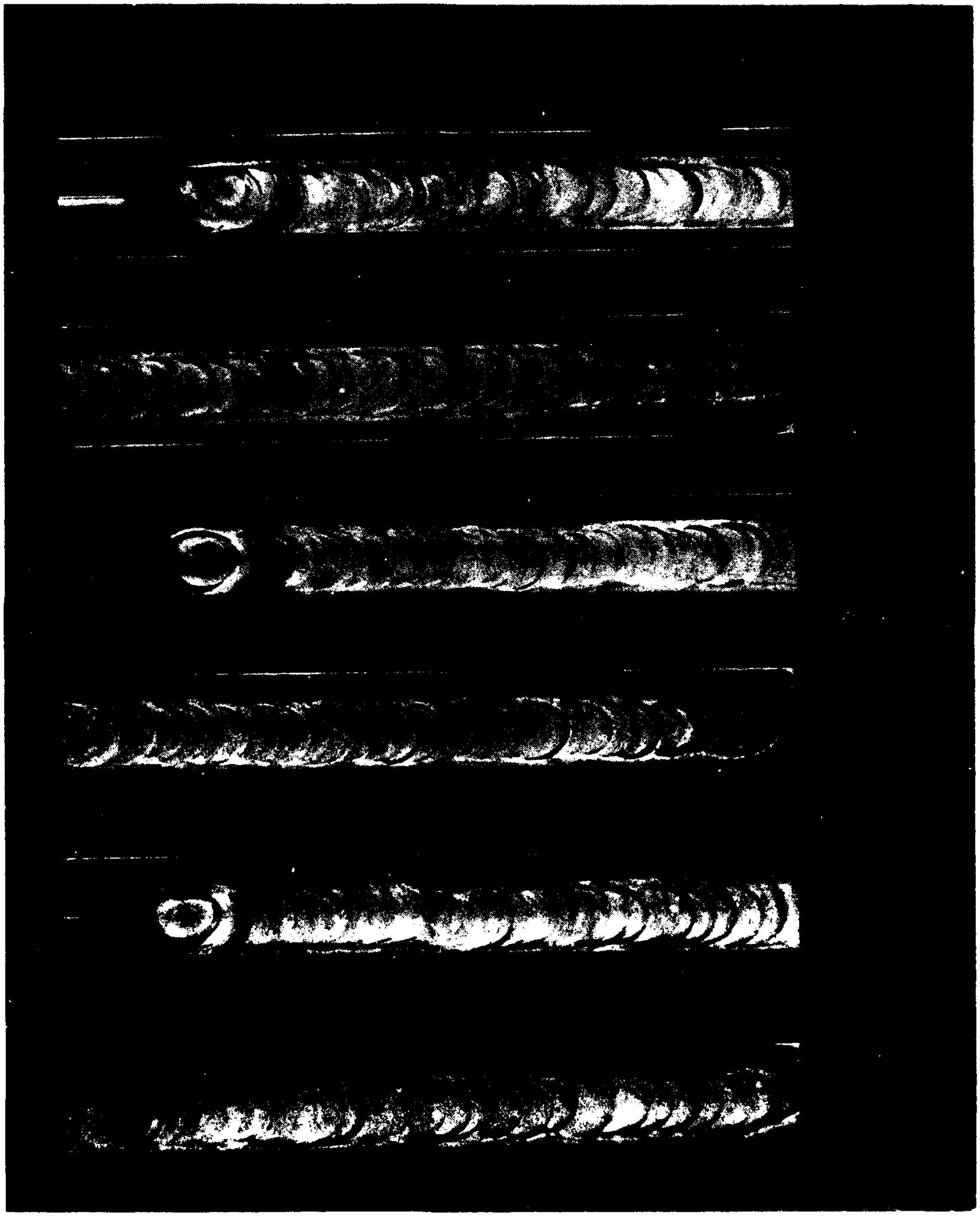

Figure 10. Aluminum Alloy Type 5086 – Specimens: Pretest

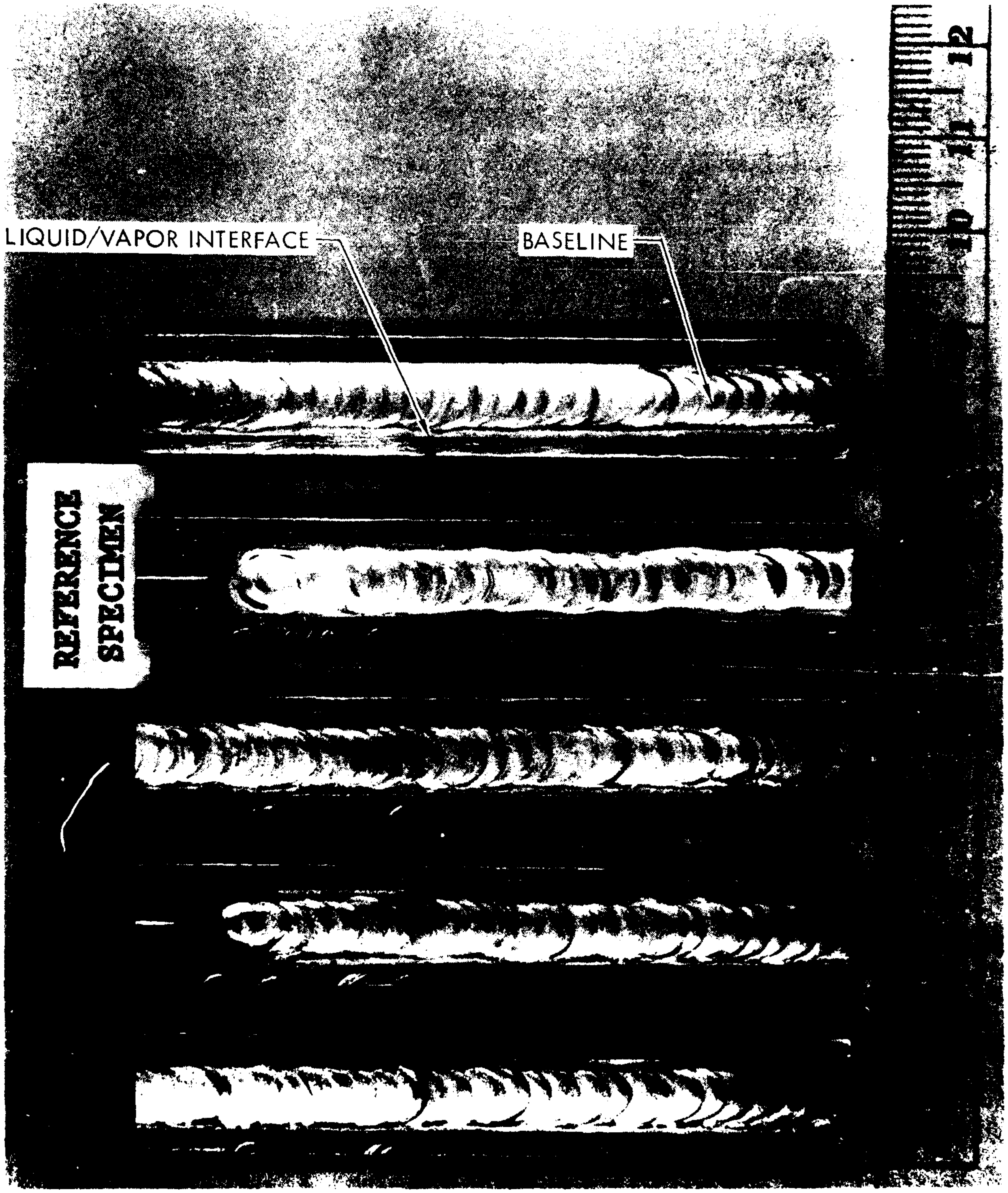

Figure 11. Aluminum Alloy Type 5086 Specimens: Posttest

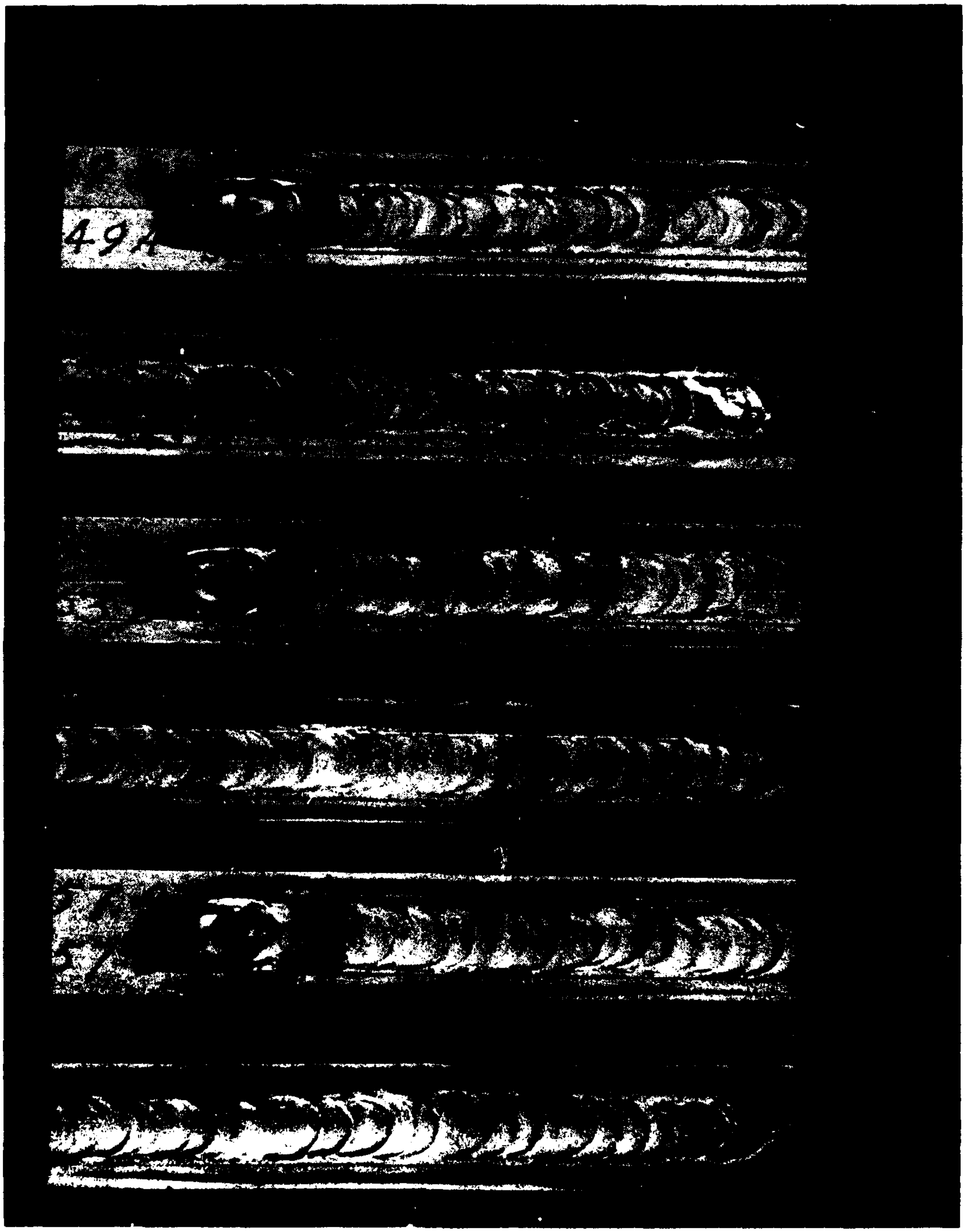

Figure 12. Aluminum Alloy Type 5456 - Specimens: Pretest

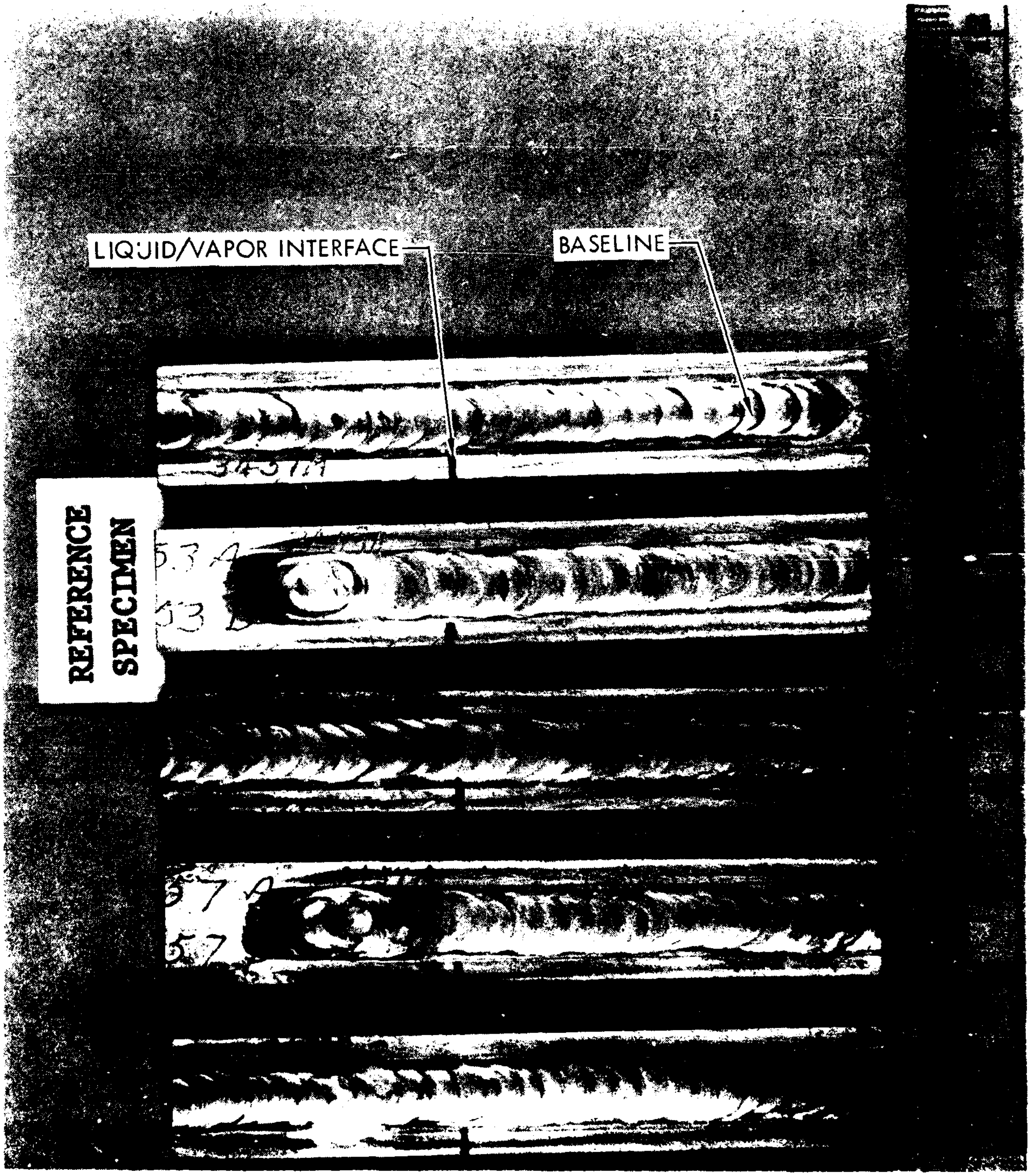

Figure 13. Aluminum Alloy Type 5456 – Specimens: Posttest

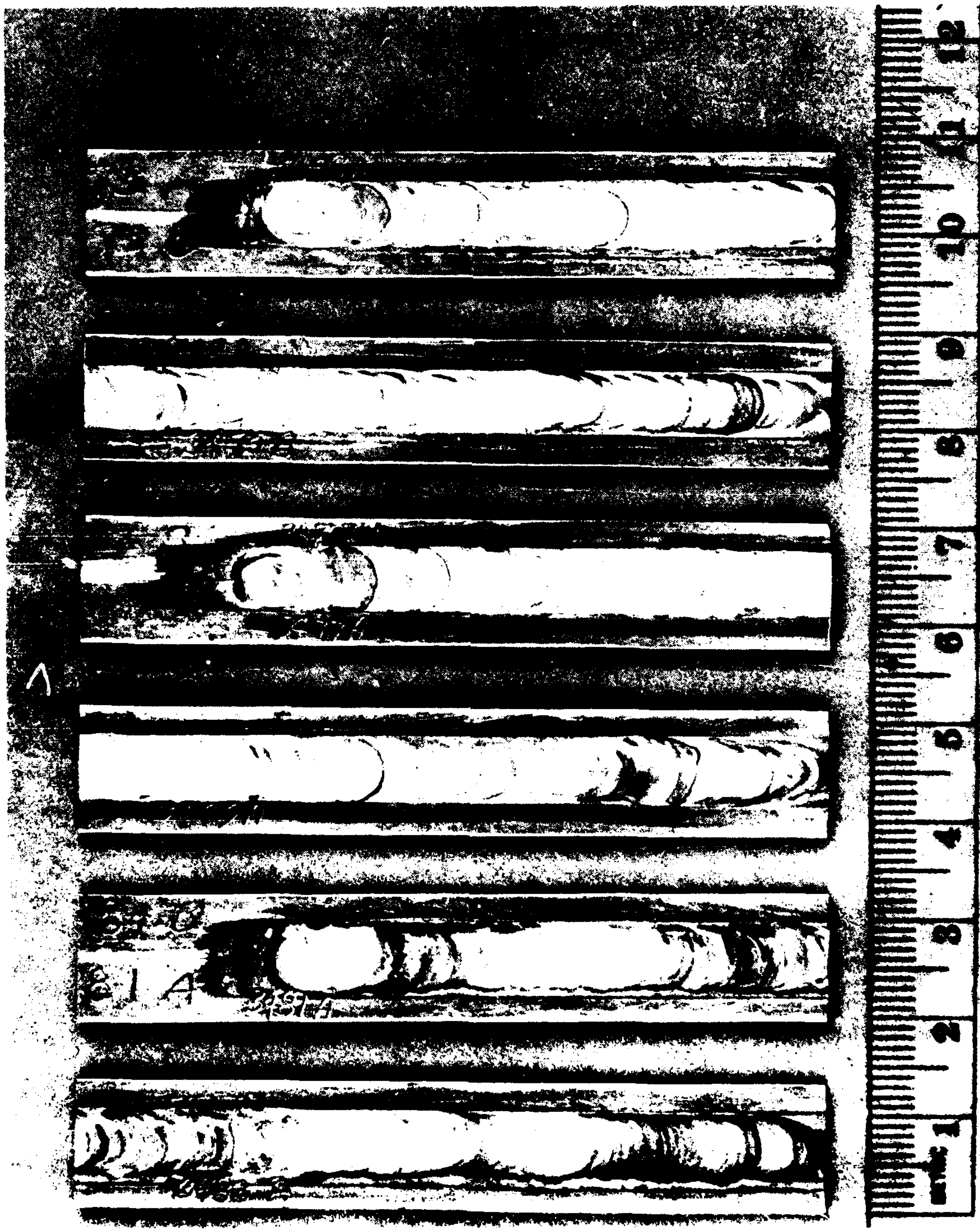

Figure 14. Aluminum Alloy Type 6061 – Specimens: Pretest

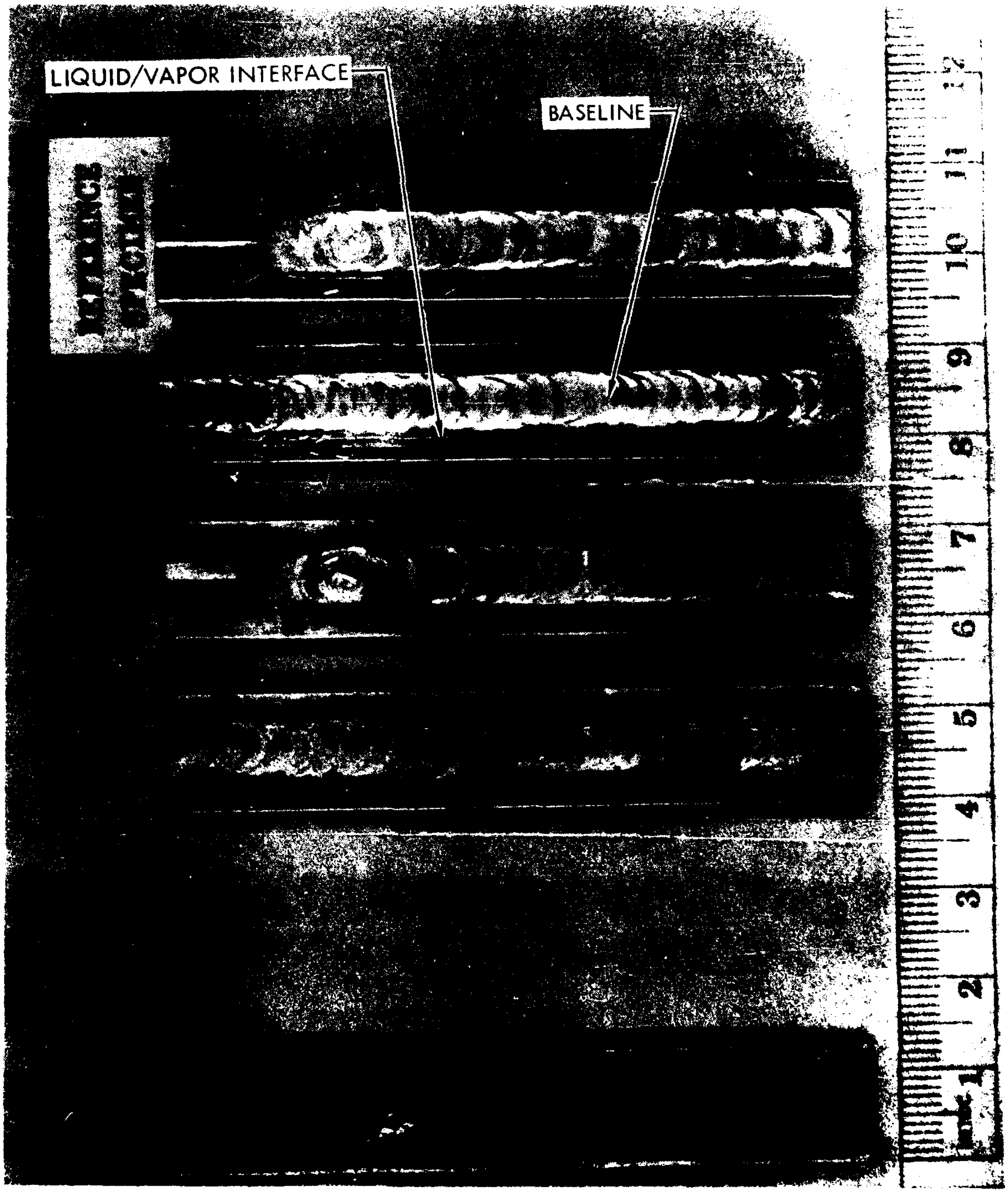

Figure 15. Aluminum Alloy Type 6061 – Specimens: Posttest

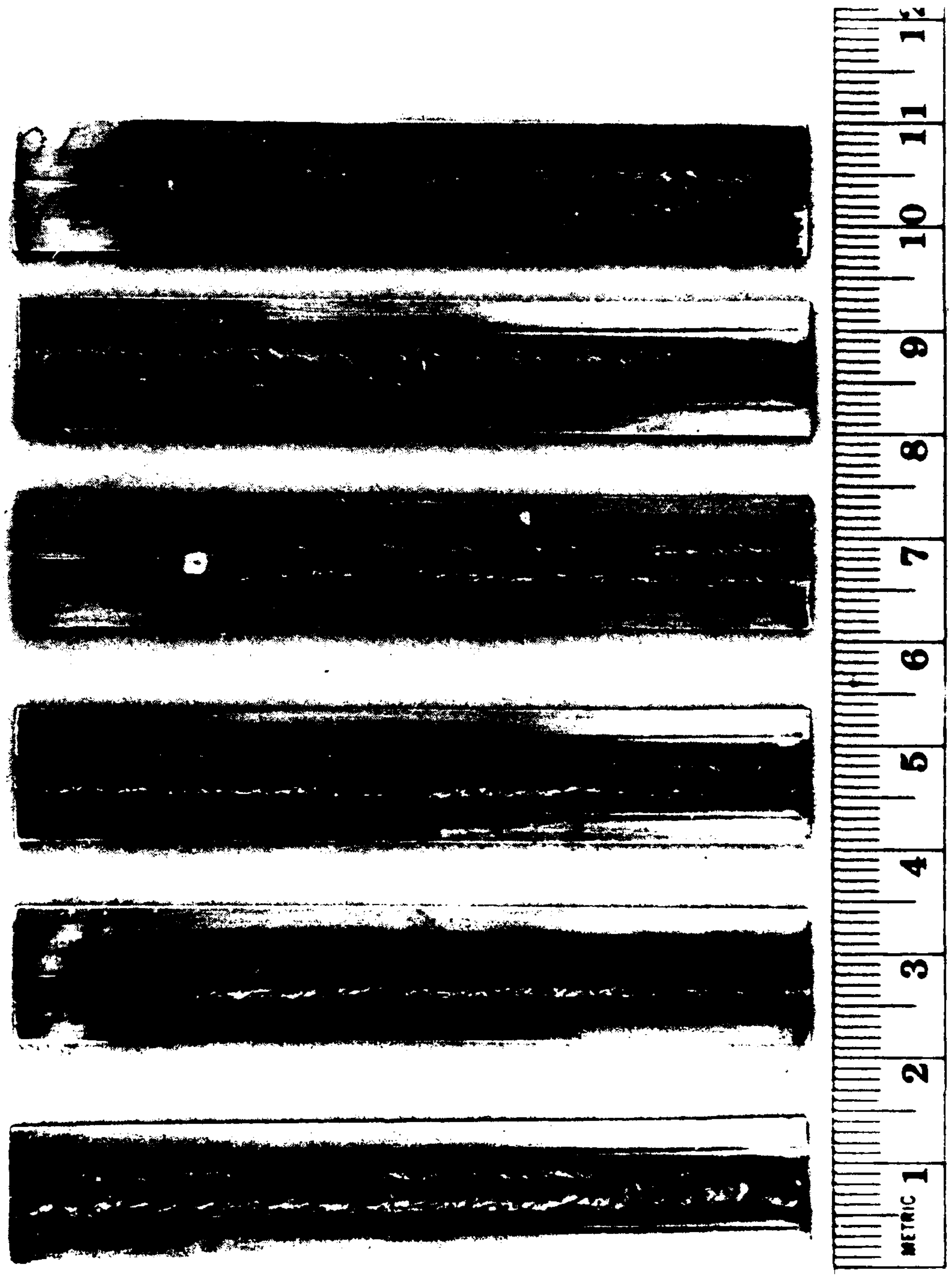

Figure 16. CRES Type 316 Specimens: Pretest

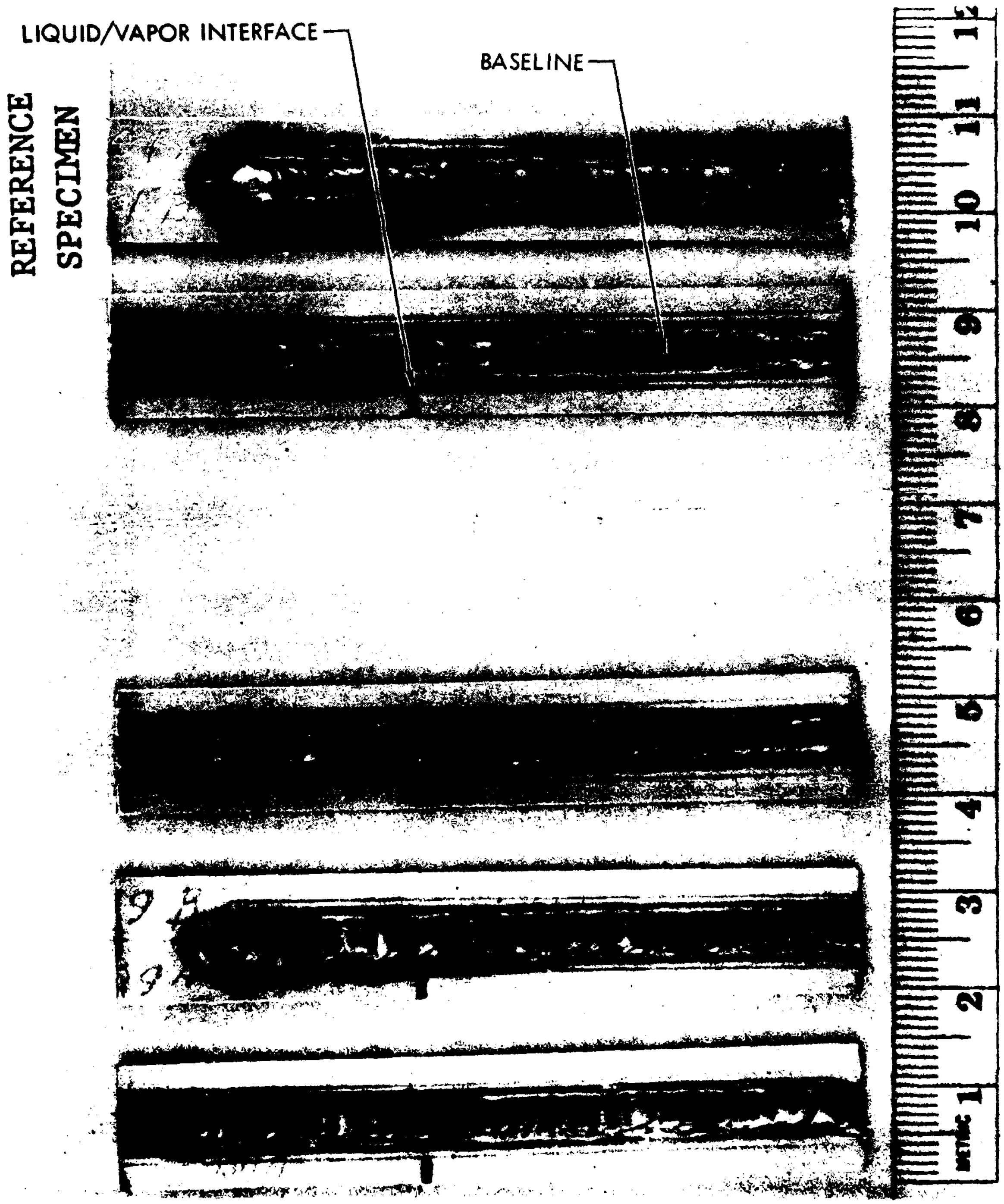

Figure 17. CRES Type 316 Specimens: Posttest

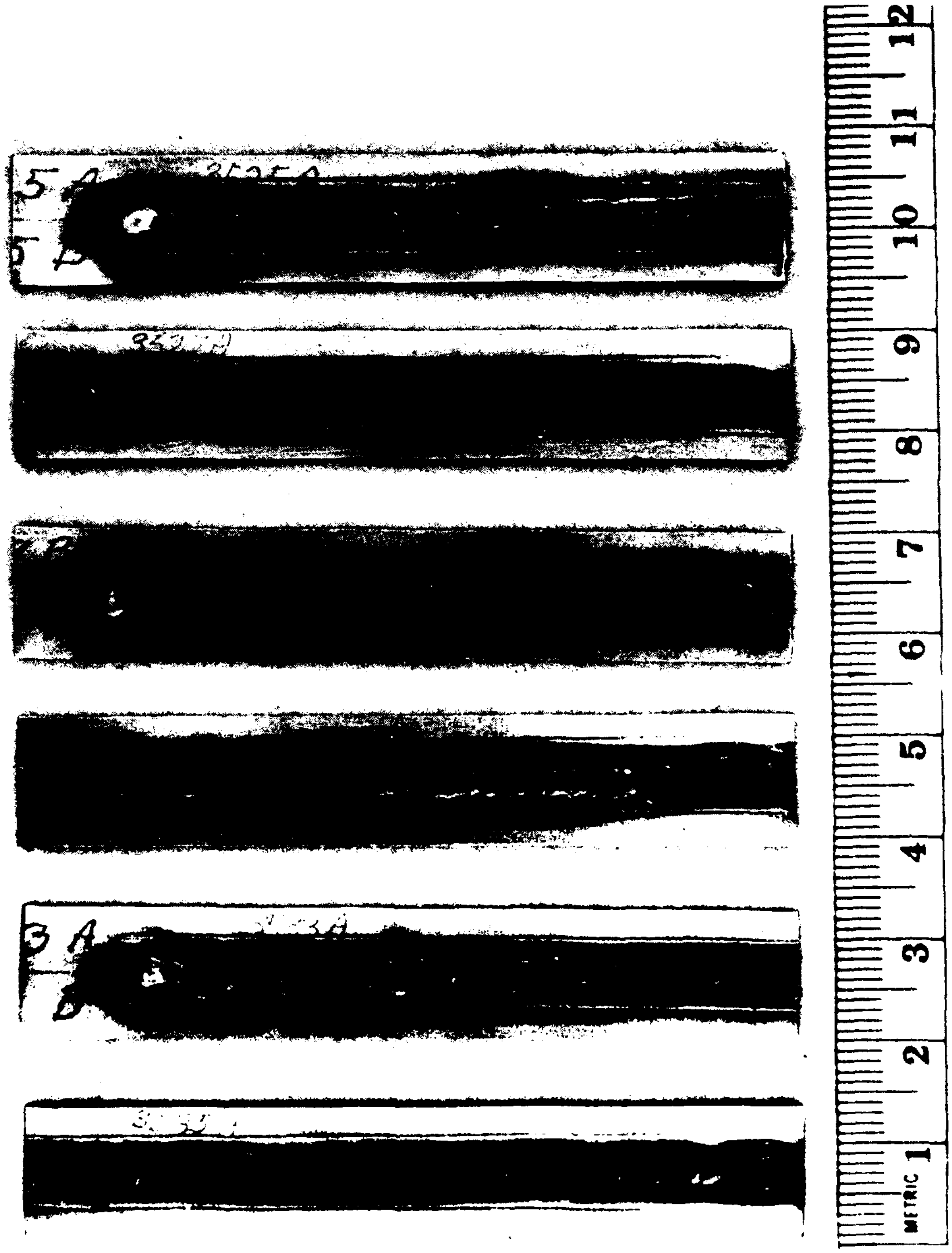

Figure 18. CRES Type 316L Specimens: Pretest

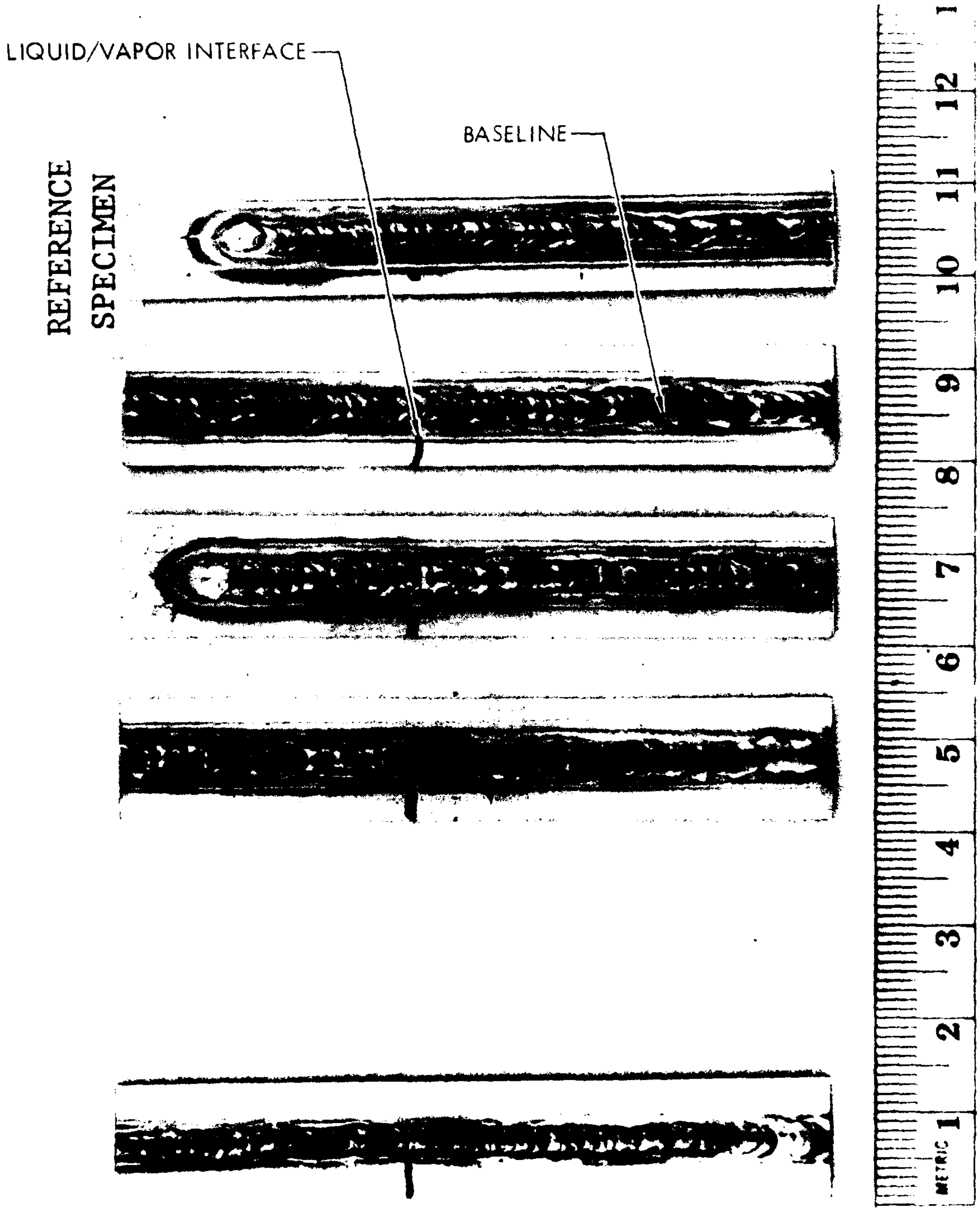

Figure 19. CRES Type 316L -- Specimens: Posttest

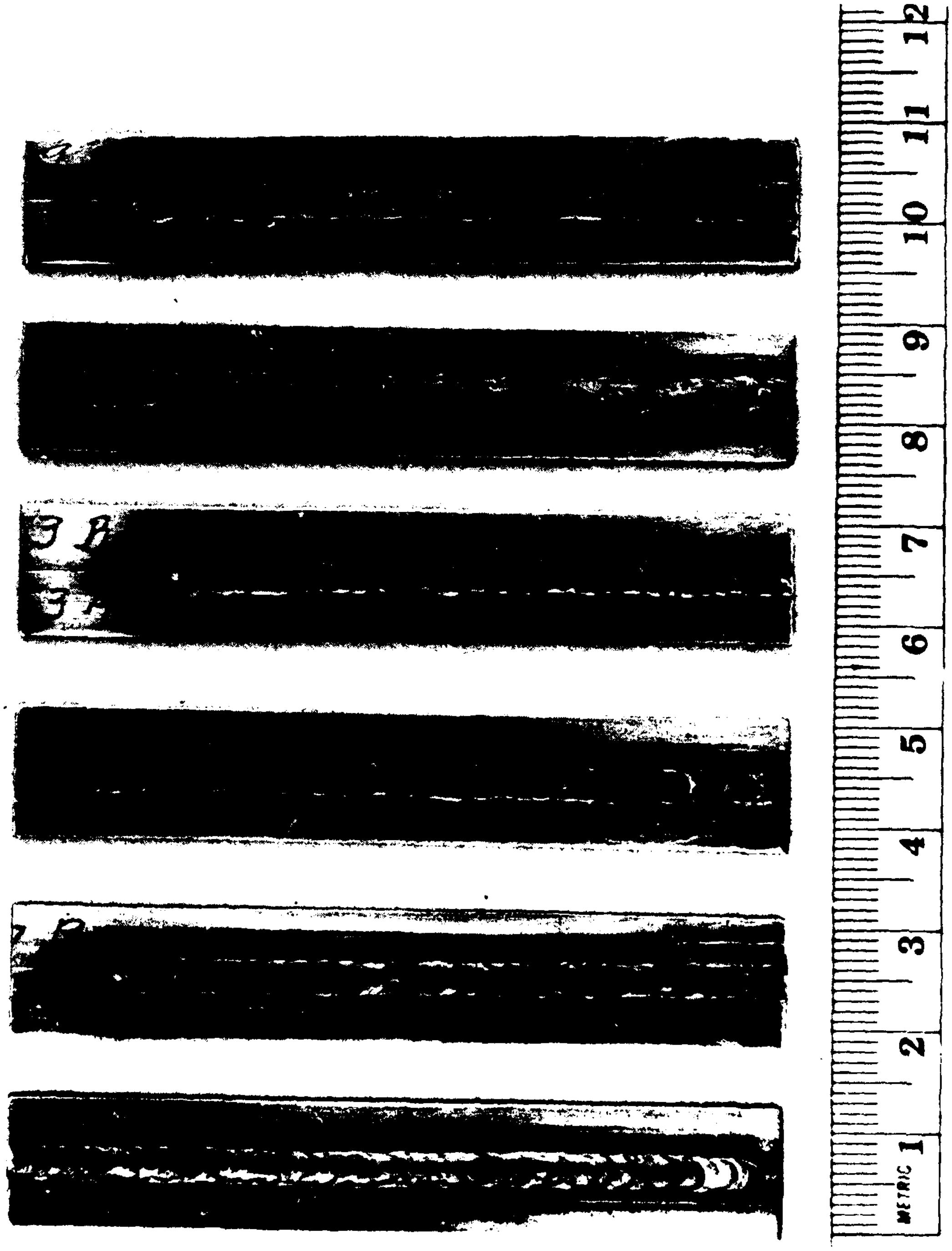

Figure 20. CRES Type 321 – Specimens: Pretest

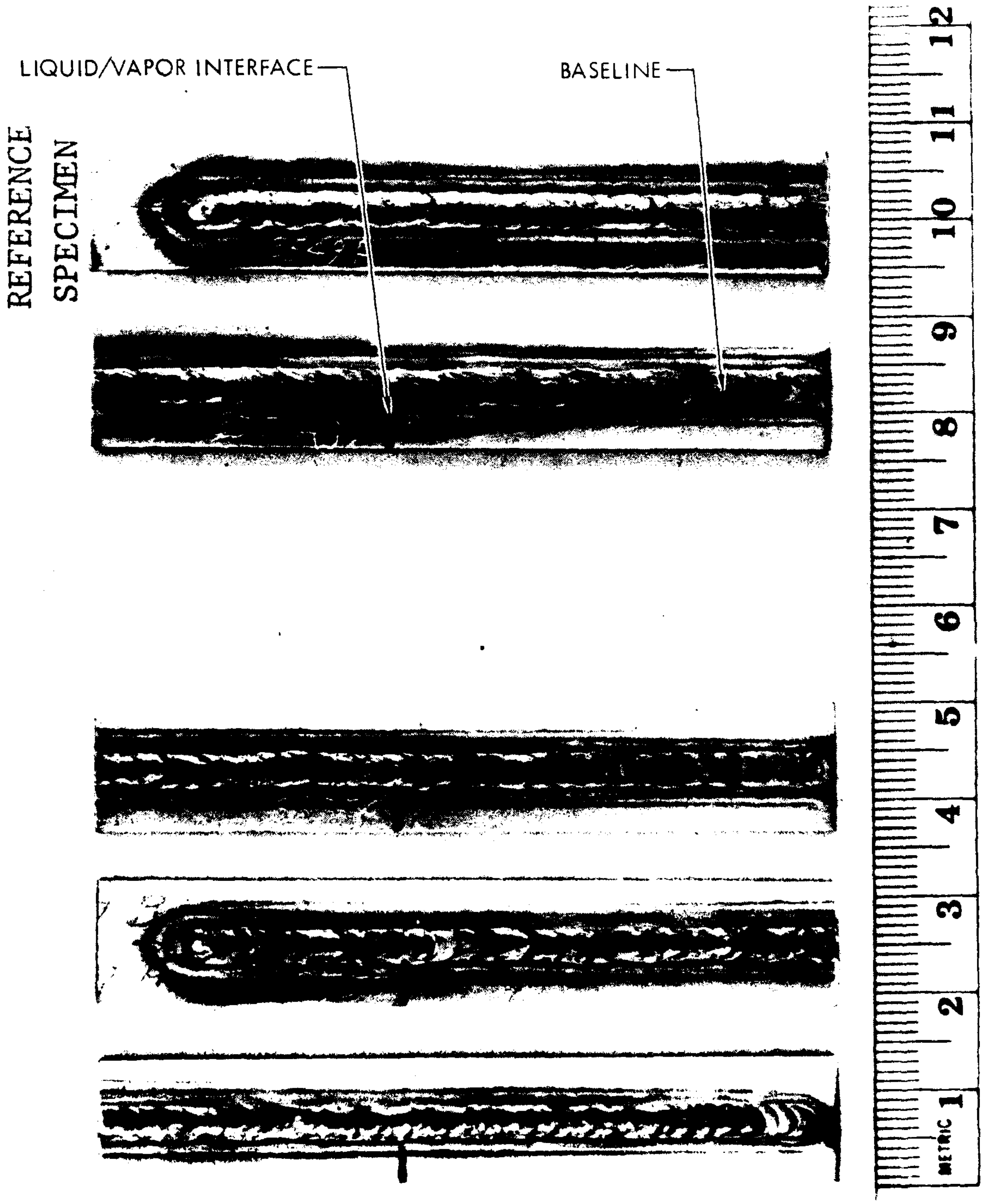

Figure 21. CRES Type 321 — Specimens: Posttest

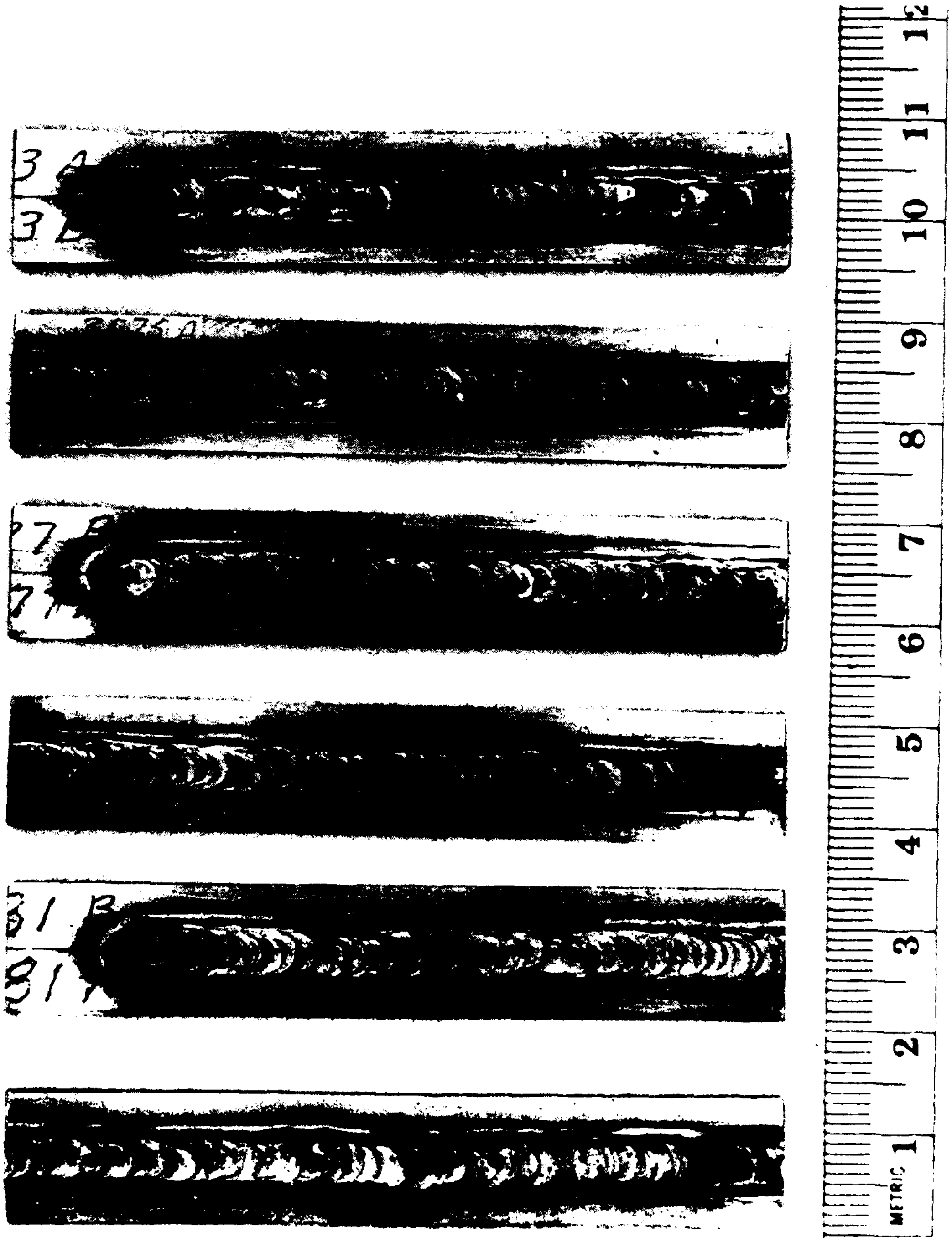

Figure 22. CRES Type 430 – Specimens: Pretest

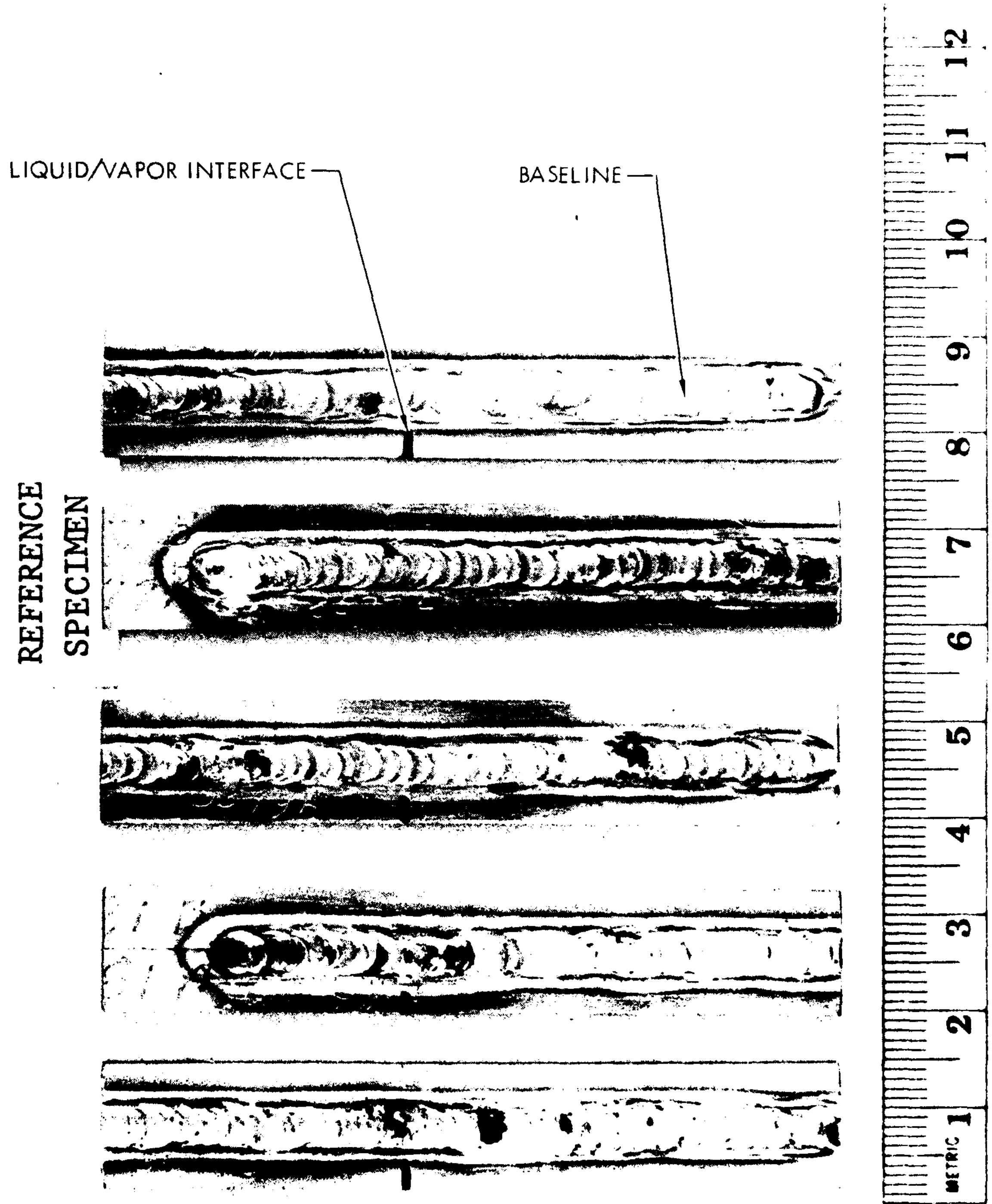

Figure 23. CRES Type 430 — Specimens: Posttest

APPENDIX A

Specimens Posttest Analyses and Results

Table A-1. Summary of Posttest Analyses and Results — Monomethylhydrazine

Specimen Number	Specimen			Capsule Pressure,[b] N/cm² at 71°C	Propellant		
	Material[a]	Weight Change, mg	Remarks		Type	Decomposition, %	Remarks
3403	Al 5052	0	No visible tarnish	6.5	Mil. Spec.	0.015	Clear, colorless
3405	Al 5052	—[c]	—	—	None[d]	—	—
3407	Al 5052	+2.6	Blue-grey tarnish in vapor phase Faint line at L/V interface	<7.0[e]	Doped	—	Clear, colorless
3409	Al 5052	+1.0	Faint blue tarnish in vapor phase	<7.0[e]	Doped	—	Clear, colorless
3411	Al 5052	+0.3	No visible tarnish	6.6	Doped	0.015	Clear, colorless
3427	Al 5086	-0.1	No visible tarnish	6.6	Mil. Spec.	0.015	Clear, colorless
3429	Al 5086	—	—	—	None[d]	—	—
3431	Al 5086	+0.6	Faint yellow tarnish in vapor phase	<7.0[e]	Doped	—	Clear, colorless
3433	Al 5086	+0.4	Faint yellow tarnish in vapor phase	<7.0[e]	Doped	—	Clear, colorless
3435	Al 5086	+0.2	No visible tarnish	6.6	Doped	0.016	Clear, colorless
3451	Al 5456	+0.2	No visible tarnish	6.6	Mil. Spec.	0.016	Clear, colorless
3453	Al 5456	—	—	-	None[d]	—	—
3455	Al 5456	+0.6	No visible tarnish	6.6	Doped	0.016	Clear, colorless
3457	Al 5456	+0.4	Faint tarnish in vapor phase	<7.0[e]	Doped	—	Clear, colorless
3459	Al 5456	+0.6	Faint tarnish	<7.0[e]	Doped	-	Clear, colorless
3473	Al 6061	—	—	—	None[d]		—
3475	Al 6061	-0.1	No visible tarnish	6.6	Mil. Spec.	0.015	Clear, colorless
3477	Al 6061	+0.2	Faint tarnish	6.6	Doped	0.015	Clear, colorless
3479	Al 6061	+0.3	Faint tarnish	<7.0[e]	Doped	—	Clear, colorless
3483	Al 6061	+1.2	Faint tarnish	<7.0[e]	Doped	-	Clear, colorless
3501	CRES 316	—	-	—	None[d]	—	—
3503	CRES 316	-0.3	No visible tarnish	6.8	Mil. Spec.	0.018	Clear, colorless

Table A-1. (contd)

Specimen Number	Specimen			Capsule Pressure,[b] N/cm^2 at 71°C	Propellant		
	Material[a]	Weight Change, mg	Remarks		Type	Decomposition, %	Remarks
3507	CRES 316	-0.1	No visible tarnish	$<$7.0[e]	Doped	–	Faint yellow tinge
3509	CRES 316	-0.2	No visible tarnish	$<$7.0[e]	Doped	–	Clear, colorless
3511	CRES 316	-0.3	No visible tarnish	7.3	Doped	0.032	Faint yellow tinge
3525	CRES 316L	–	–	–	None[d]	–	–
3527	CRES 316L	-0.2	No visible tarnish	6.9	Mil. Spec.	0.021	Clear, colorless
3529	CRES 316L	-0.4	No visible tarnish	$<$7.0[e]	Doped	–	Faint yellow tinge
3531	CRES 316L	-0.2	No visible tarnish	$<$7.0[e]	Doped	–	Faint yellow tinge
3535	CRES 316L	-0.4	No visible tarnish	7.3	Doped	0.035	Faint yellow tinge
3549	CRES 321	–	–	–	None[d]	–	–
3551	CRES 321	-0.2	No visible tarnish	6.8	Mil. Spec.	0.017	Clear, colorless
3555	CRES 321	-0.3	No visible tarnish	6.9	Doped	0.019	Clear, colorless
3557	CRES 321	-0.5	No visible tarnish	$<$7.0[e]	Doped	–	Faint yellow tinge
3559	CRES 321	-0.3	No visible tarnish	$<$7.0[e]	Doped	–	Faint yellow tinge
3575	CRES 430	-0.2	No visible tarnish	6.8	Mil. Spec.	0.015	Light yellow color
3577	CRES 430	–	–	–	None[d]	–	–
3579	CRES 430	-0.4	No visible tarnish	$<$7.0[e]	Doped	–	Faint yellow tinge
3581	CRES 430	-0.6	No visible tarnish	–	Doped	–	Faint yellow tinge
3583	CRES 430	-0.5	No visible tarnish	6.8	Doped	0.016	Light yellow color
3491	–	–	–	6.1	Mil. Spec.	0.004	Clear, colorless
3493	–	–	–	6.2	Mil. Spec.	0.005	Clear, colorless
3495	–	–	–	6.1	Mil. Spec.	0.004	Clear, colorless

Table A-1. (contd)

Specimen Number	Specimen			Capsule Pressure,[b] N/cm² at 71°C	Propellant		
	Material[a]	Weight Change, mg	Remarks		Type	Decomposition, %	Remarks
3591	–	–	–	6.2	Doped	0.006	Clear, colorless
3593	–	–	–	6.2	Doped	0.005	Clear, colorless
3595	–	–	–	6.2	Doped	0.005	Clear, colorless

[a]Specimen type: welded (Ref. 9); test duration: 123 days.

[b]Includes vapor pressure of MMH at 71°C (160°F): 5.3 N/cm² (7.6 psi).

[c] Not measured: data not available.

[d] Reference specimen (control).

[e] Estimated: based on opening fixture pressure gauge.

Table A-2. Summary of Detailed Posttest Analyses and Results — Monomethylhydrazine

Specimen Number	Specimen Weight: Initial, g	Specimen Weight: Change, g	Analysis of Propellant[a]: Fe + Cr + Ni, μg	Al, μg	CO_2, μg/g	H_2O, %	NH_3, %	UDMH, %	Analysis of Gas: N_2 + CH_4, cm^3 STP	N_2, mole %	CH_4, mole %
3403	4.9646	0	b	7.5	–	1.13	0.16	0.1	0.67	–	–
3405	4.8868	–		–	–	–	–	–	–	–	–
3407	4.8735	+0.0026	–	20	–	3.21	0.37	0.1	–	–	–
3409	4.8045	+0.0010		8.5	–	3.01	0.11	0.1	–	–	–
3411	5.0930	+0.0003		12.5	–	2.86	0.14	0.1	0.72	–	–
3427	4.8401	-0.0001		8	–	1.02	0.13	0.1	0.72	–	–
3429	4.7883	–		–	–	–	–	–	–	–	–
3431	4.9393	+0.0006	–	7	–	3.01	0.11	0.1	–	–	–
3433	4.9806	+0.0004	–	11	–	3.11	0.11	0.1	–	–	–
3435	4.8906	+0.0002	–	4	–	3.07	0.12	0.1	0.89	–	–
3451	5.0860	+0.0002	–	8		0.78	0.15	0.1	0.81	–	–
3453	5.2447		–		–	–	–	–	–	–	–
3455	5.2928	+0.0006		31		3.04	0.10	0.1	0.86	–	–
3457	5.2776	+0.0004		10		3.07	0.08	0.1	–	–	–
3459	5.3579	+0.0006		4		3.17	0.10	0.1	–	–	–
3473	4.5488						–	–	–	–	–
3475	4.7429	-0.0001		12		1.10	0.15	0.1	0.75	–	–
3477	4.6316	+0.0002		28	–		0.15	0.1	0.78	–	–
3479	4.8017	+0.0003	–	21		3.07	0.06	0.1	–	–	–
3483	4.9510	+0.0012	–	25		3.27	0.05	0.1	–	–	–
3501	12.4564	–	–	–	–	–	–	–	–	–	–
3503	12.5087	-0.0003	17.5	–	17	1.20	0.10	0.1	1.16	91.9	8.1
3507	12.6630	-0.0001	62	–	–	2.84	0.16	0.1	–	–	–
3509	12.5638	-0.0002	87	–	–	2.92	0.24	0.1	–	–	–
3511	12.5901	-0.0003	87	–	450	3.18	0.12	0.1	3.2	98.3	1.7
3525	12.7909	–	–	–	–	–	–	–	–	–	–
3527	12.9461	-0.0002	30	–	17	0.83	0.07	0.1	1.62	93.4	6.6
3529	12.9204	-0.0004	84	–	–	3.41	0.26	0.1	–	–	–
3531	12.7737	-0.0002	131	–	–	–	–	–	–	–	–

Table A-2. (contd)

Specimen Number	Specimen Weight: Initial, g	Specimen Weight: Change, g	Analysis of Propellant[a]: Fe + Cr + Ni, μg	Al, μg	CO_2, μg/g	H_2O, %	NH_3, %	UDMH, %	Analysis of Gas: N_2 + CH_4, cm^3 STP	N_2, mole %	CH_4, mole %
3535	12.9914	-0.0004	118	–	470	2.95	0.13	0.1	3.50	98.9	1.1
3549	13.0416	–	–	–	–	–	–	–	–	–	–
3551	13.0555	-0.0002	81	–		1.07	0.14	0.1	0.97	–	–
3555	13.2445	-0.0003	112	–	–	–	–	–	1.29	–	–
3557	13.0801	-0.0005	176	–	–	3.37	0.07	0.1	–	–	–
3559	13.1740	-0.0003	95	–	–	3.10	0.07	0.1	–	–	–
3575	12.2254	-0.0002	30	–	–	1.08	0.09	0.1	0.78	–	–
3577	11.8821	–	–	–		–	–	–	–	–	–
3579	11.7549	-0.0004	94	–	–	3.18	0.38	0.1	–	–	–
3581	11.9487	-0.0006	124	–	–	3.20	0.38	0.1	–	–	–
3583	11.8856	-0.0005	127	–	–	3.06	0.05	0.1	0.85	–	–
3491	–	–	–	–	–	1.10	0.10	0.1	0.61	–	–
3493	–	–	–	–		0.94	0.10	0.1	0.77	–	–
3495		–	–	–	–	1.24	0.11	0.1	0.62	–	–
3591					–	3.10	0.07	0.1	0.80	–	–
3593	–	–	–	–	–	3.02	0.05	0.1	0.72	–	–
3595	–			–	–	2.99	0.08	0.1	0.77	–	–
Pretest baseline			8	2	15	1.06	0.14	0.1	–	–	–
Pretest doped	–	–	–	–	525	3.0	–	–	–	–	–

[a]Each capsule contained 20.0 ml MMH; density 0.873 at 25°C.

[b]– Not measured: data not available.

APPENDIX B

Scanning Electron Micrographs of Aluminum Alloy Specimens:

1. Reference Specimen — Control
2. Propellant MMH — Baseline
3. Propellant MMH — Contaminated

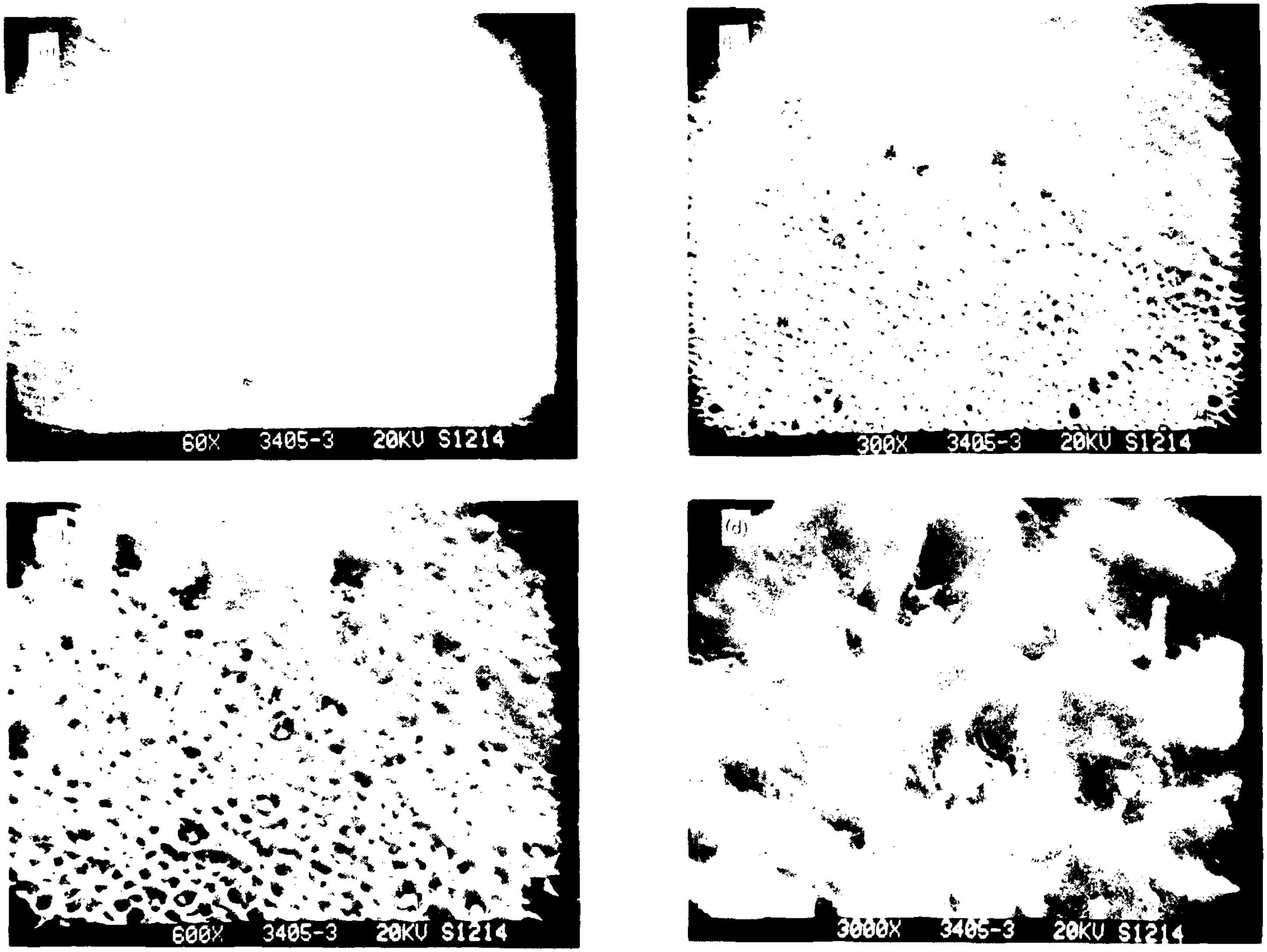

Figure B-1. Scanning Electron Micrography of Aluminum Alloy Type 5052 — Reference Specimen: Control; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

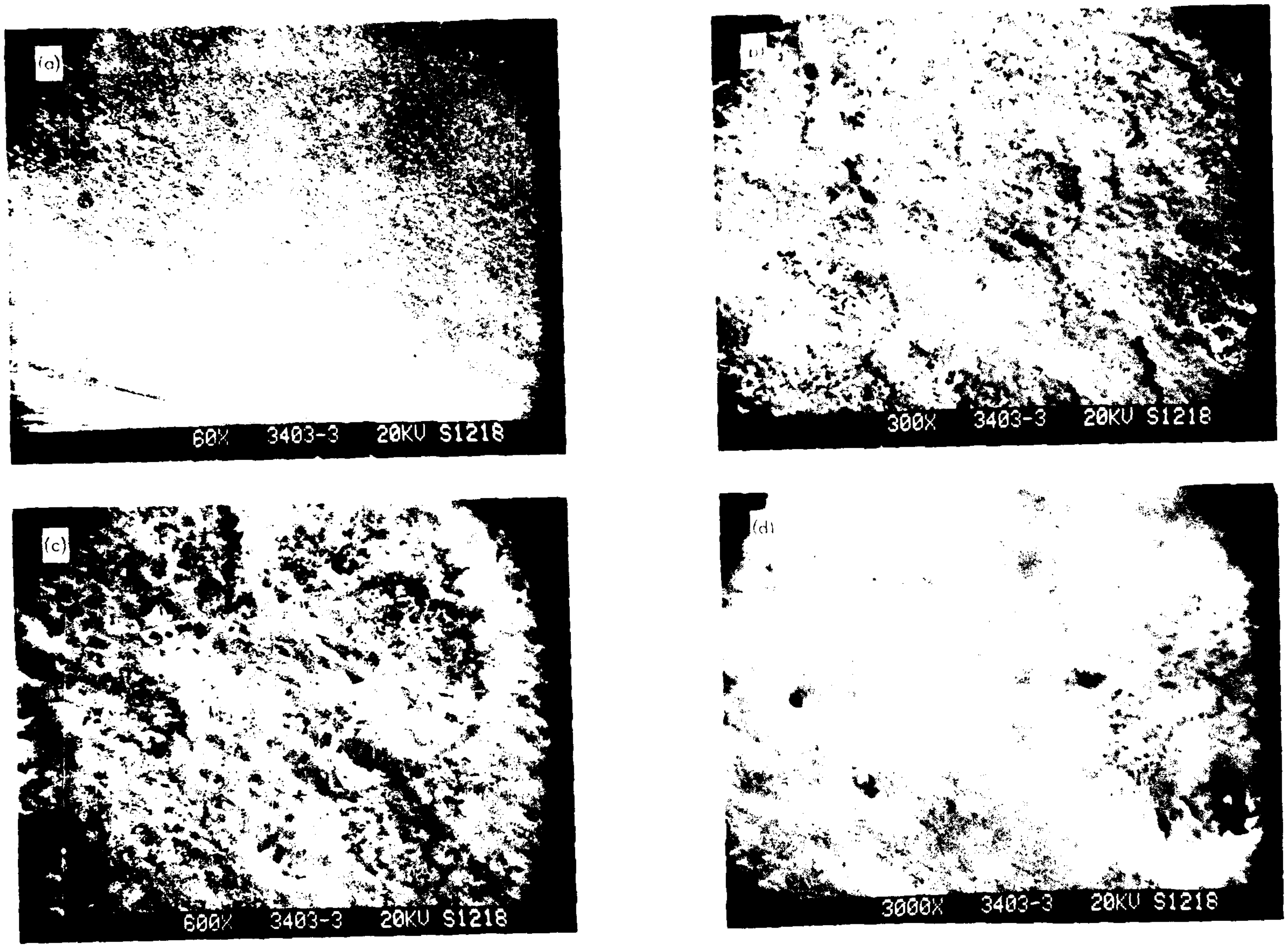

Figure B-2. Scanning Electron Micrography of Aluminum Alloy Type 5052 - Specimen Exposed to Baseline MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

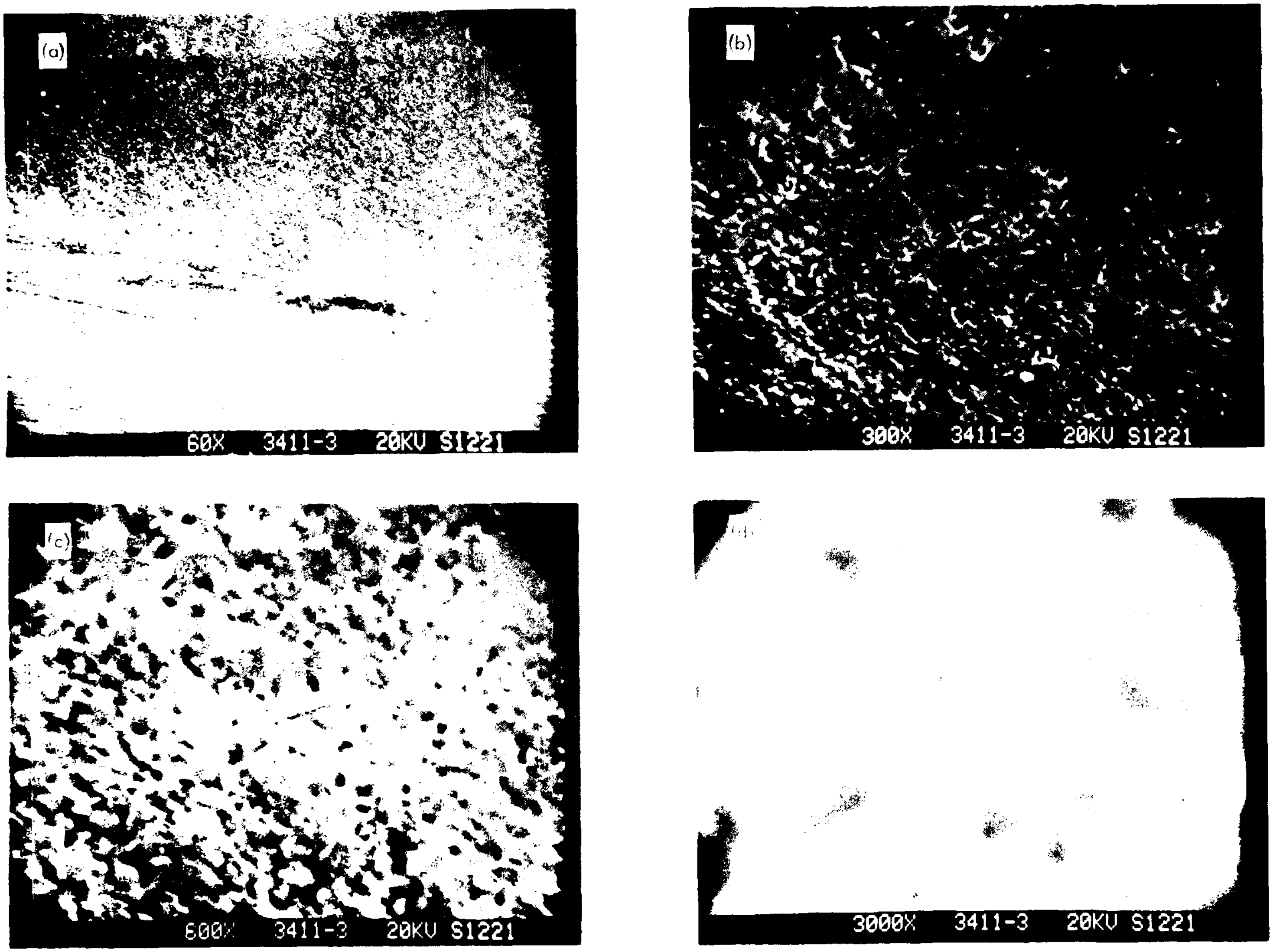

Figure B-3. Scanning Electron Micrography of Aluminum Alloy Type 5052 — Specimen Exposed to Contaminated MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

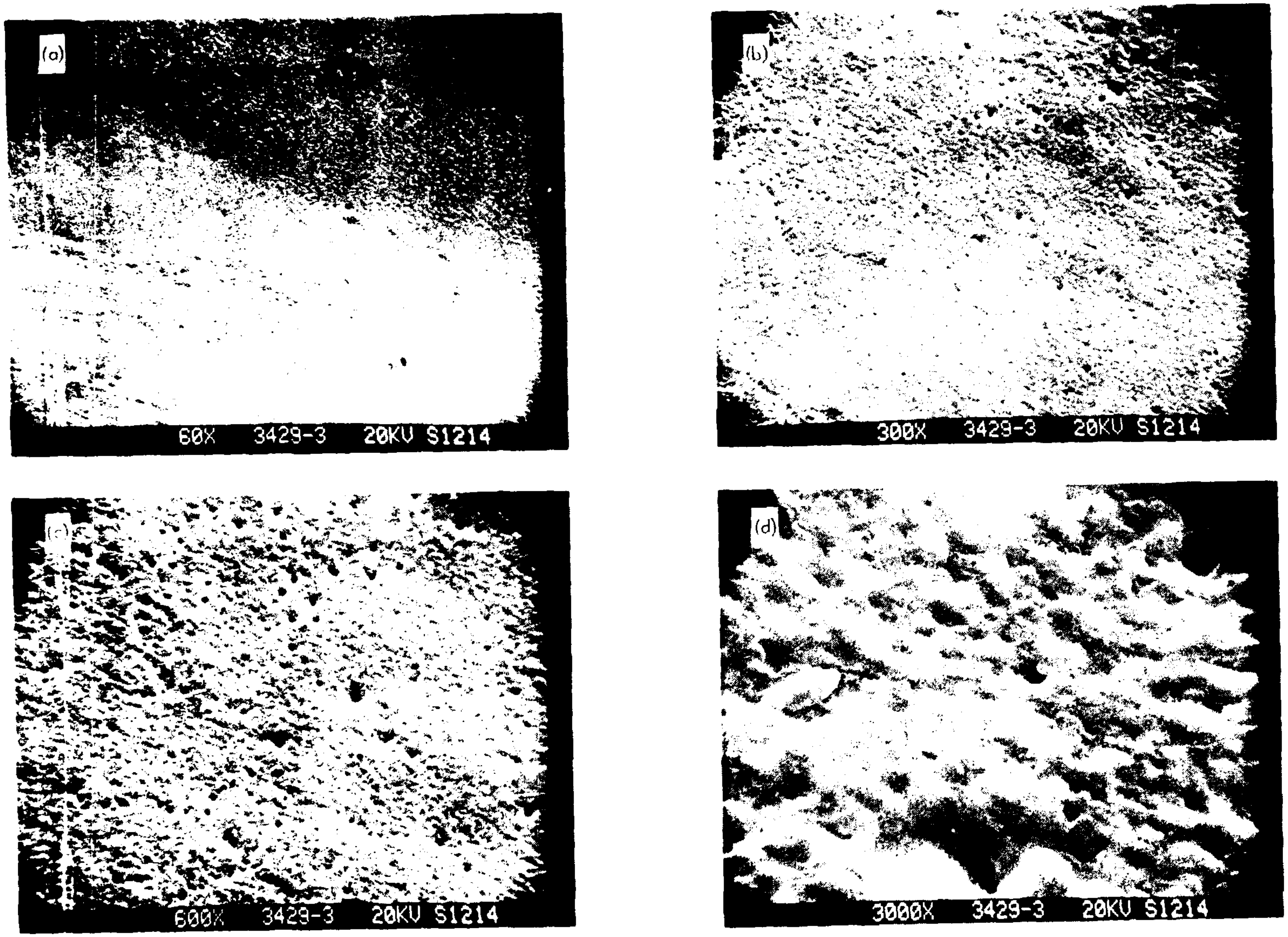

Figure B-4. Scanning Electron Micrography of Aluminum Alloy Type 5086 — Reference Specimen: Control; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

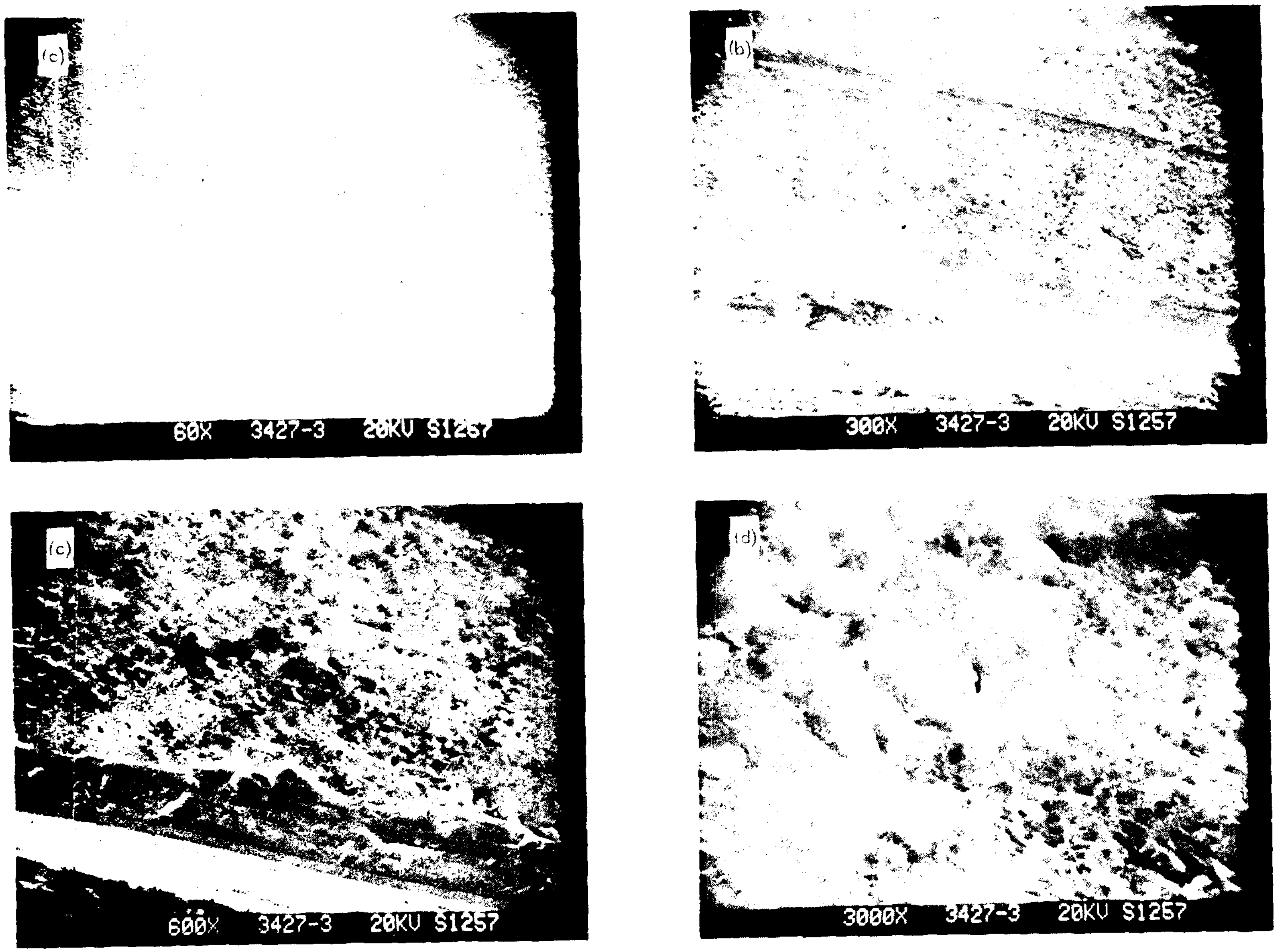

Figure B-5. Scanning Electron Micrography of Aluminum Alloy Type 5086 — Specimen Exposed to Baseline MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

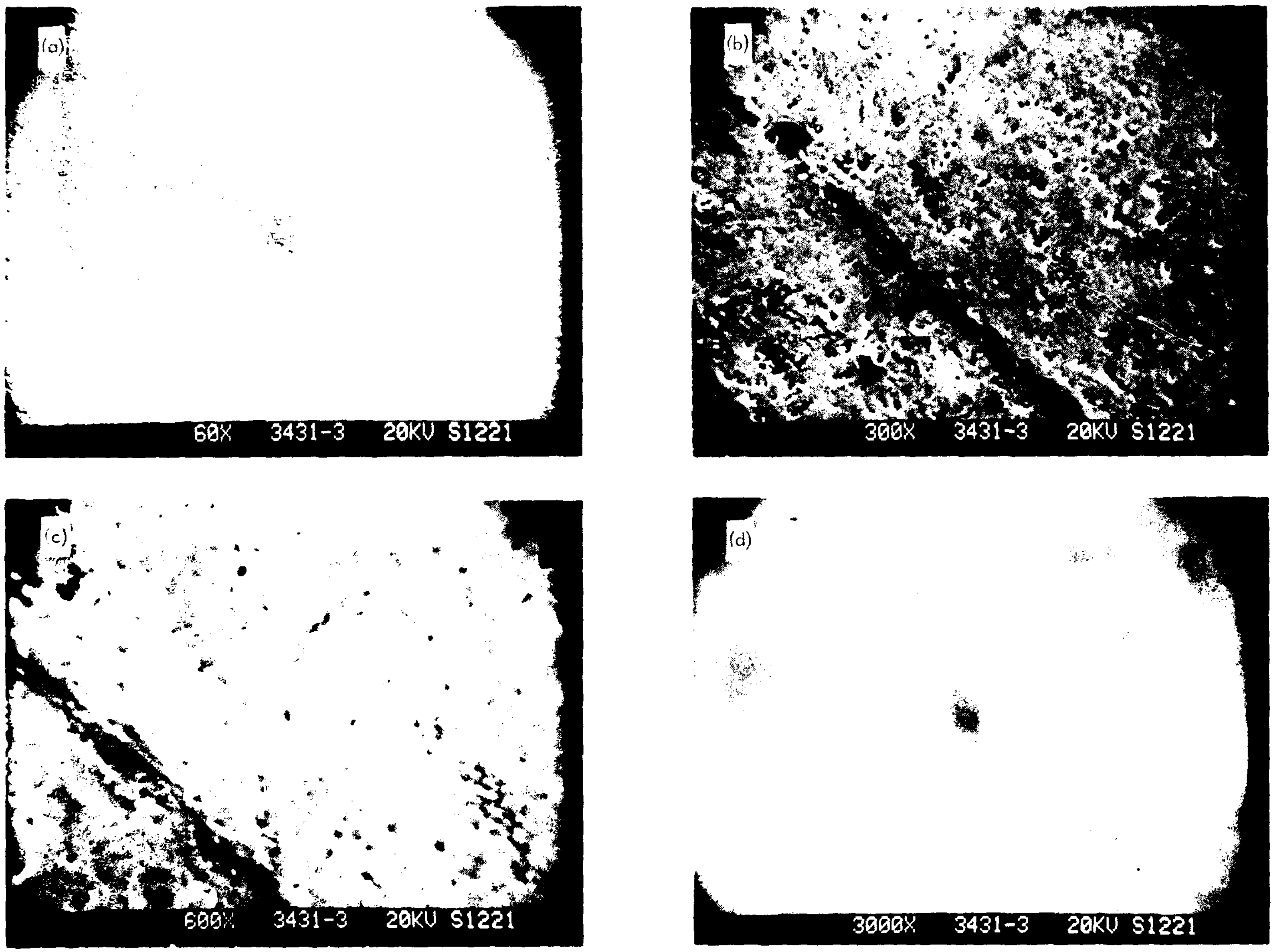

Figure B-6. Scanning Electron Micrography of Aluminum Alloy Type 5086 — Specimen Exposed to Contaminated MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

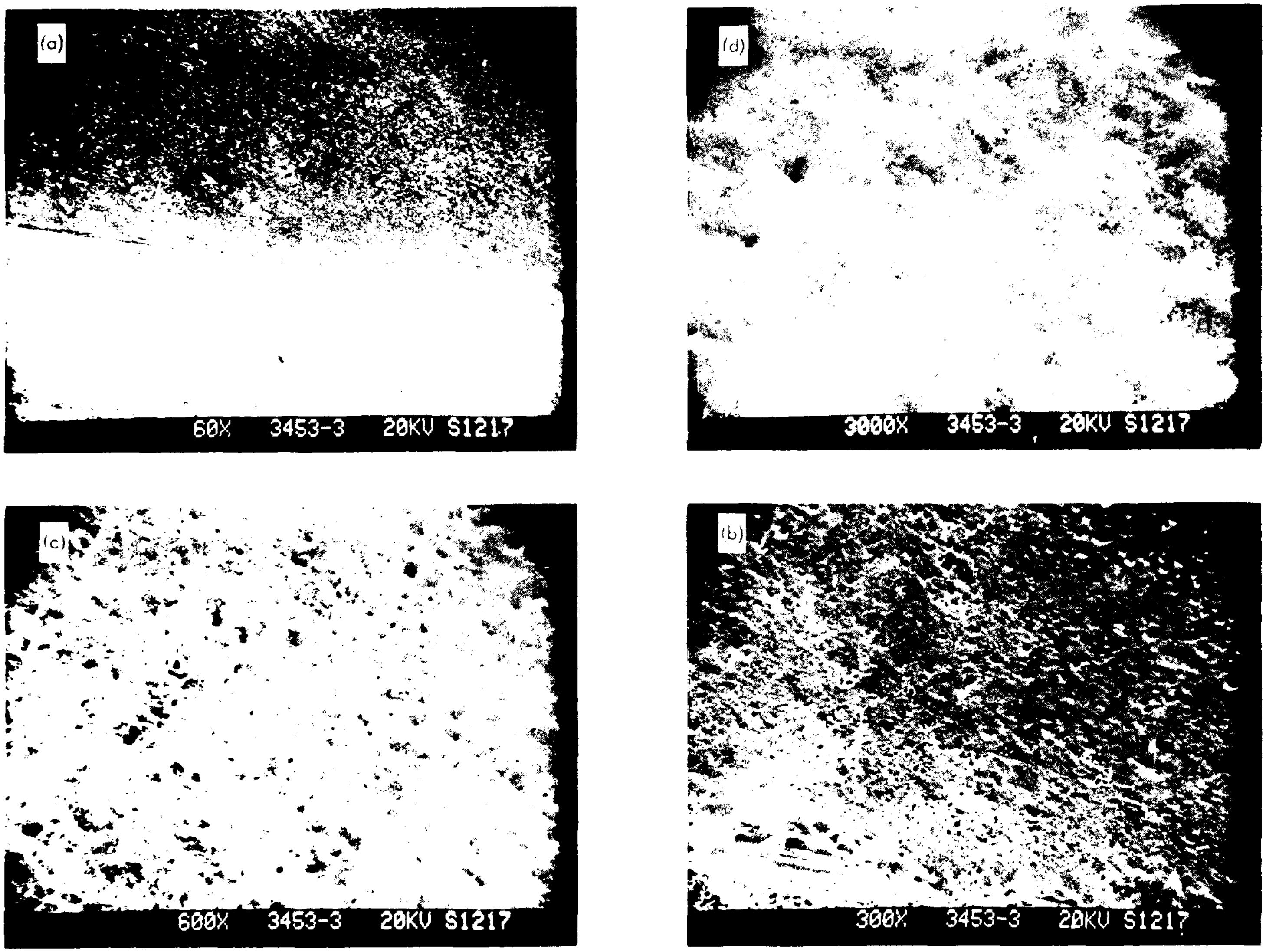

Figure B-7. Scanning Electron Micrograpny of Aluminum Alloy Type 5456 — Reference Specimen: Control; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

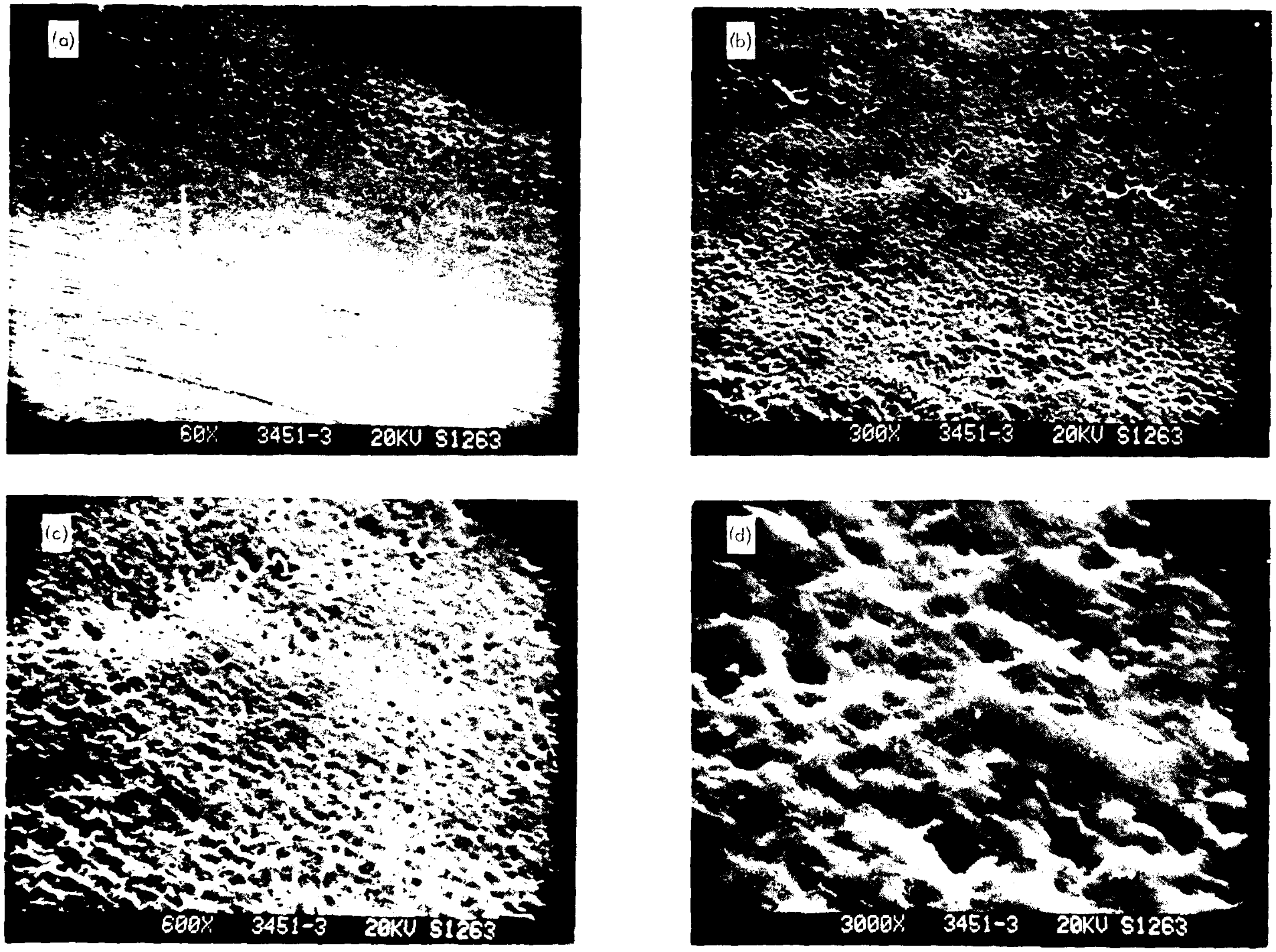

Figure B-8. Scanning Electron Micrography of Aluminum Alloy Type 5456 -- Specimen Exposed to Baseline MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

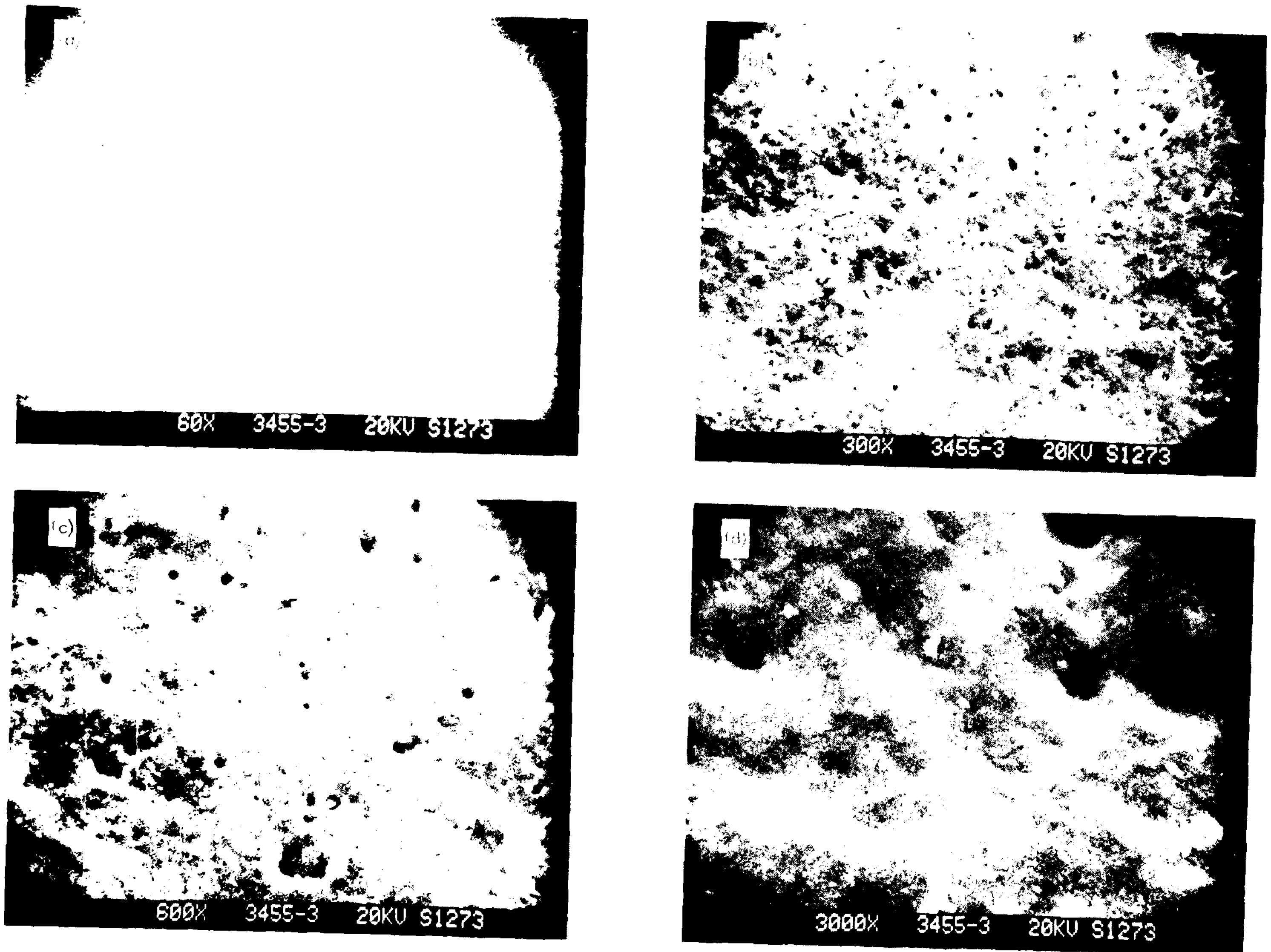

Figure B-9. Scanning Electron Micrography of Aluminum Alloy Type 5456 — Specimen Exposed to Contaminated MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

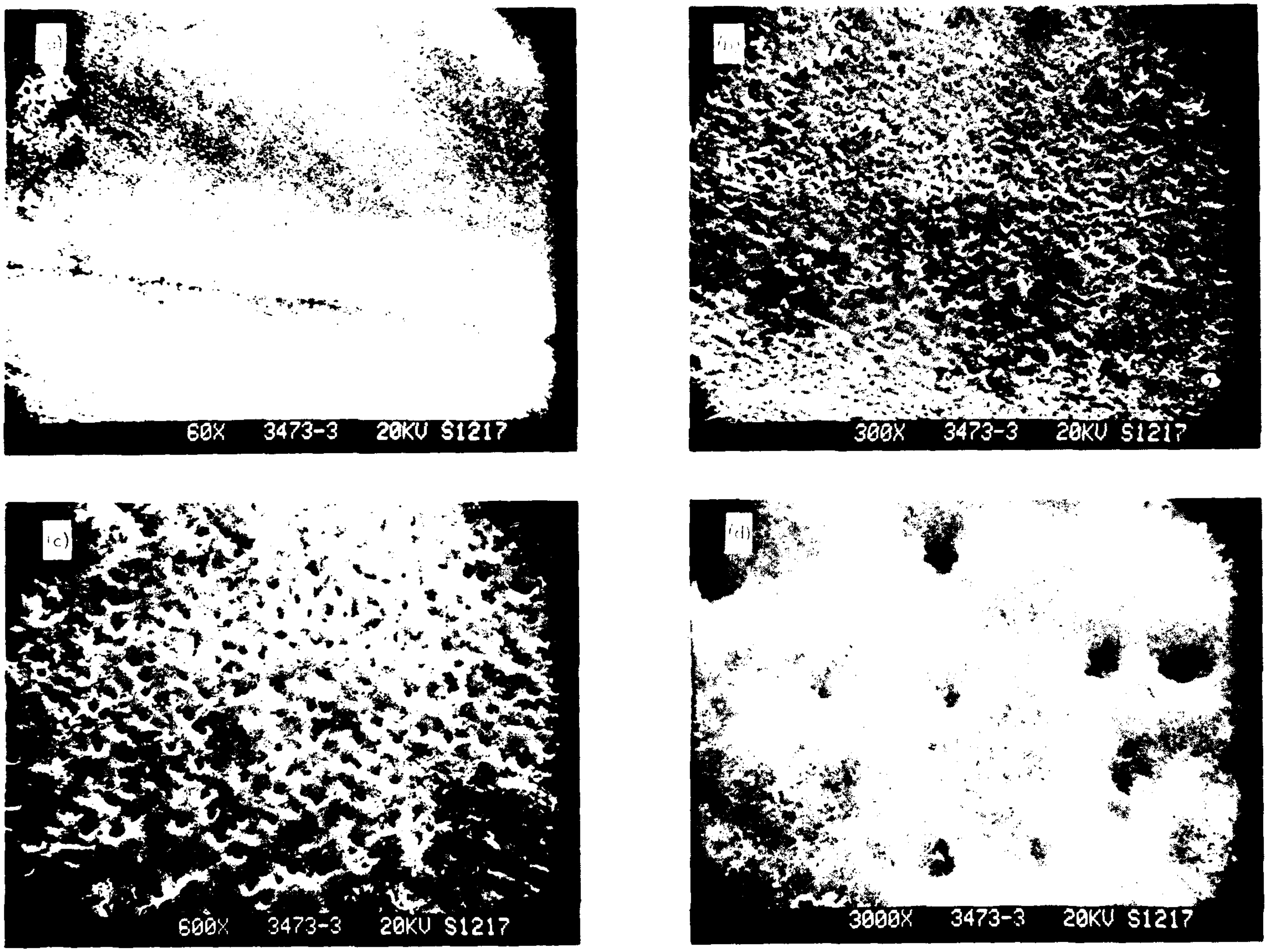

Figure B-10. Scanning Electron Micrography of Aluminum Alloy Type 6061 — Reference Specimen: Control; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

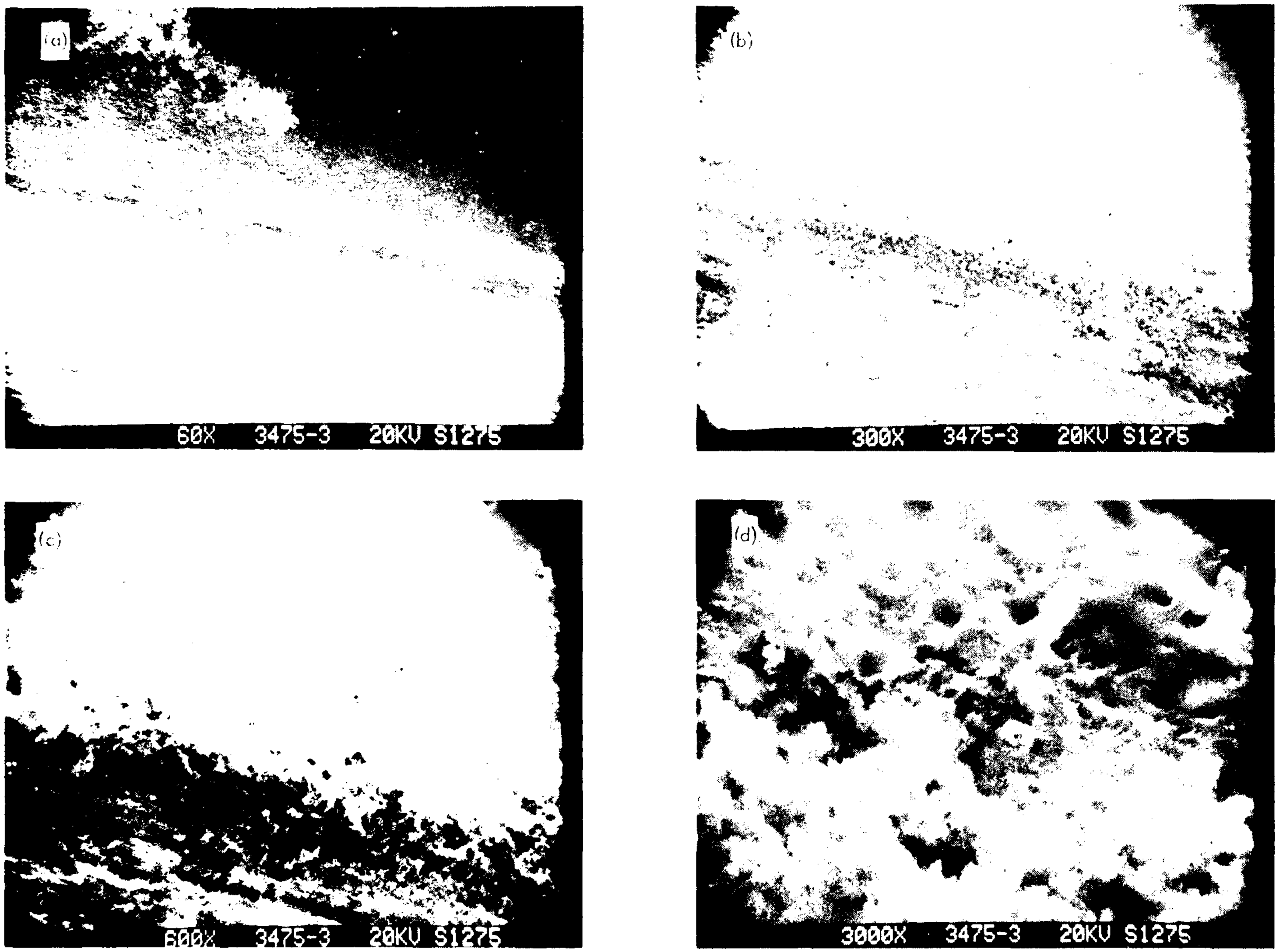

Figure B-11. Scanning Electron Micrography of Aluminum Alloy Type 6061 — Specimen Exposed to Baseline MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

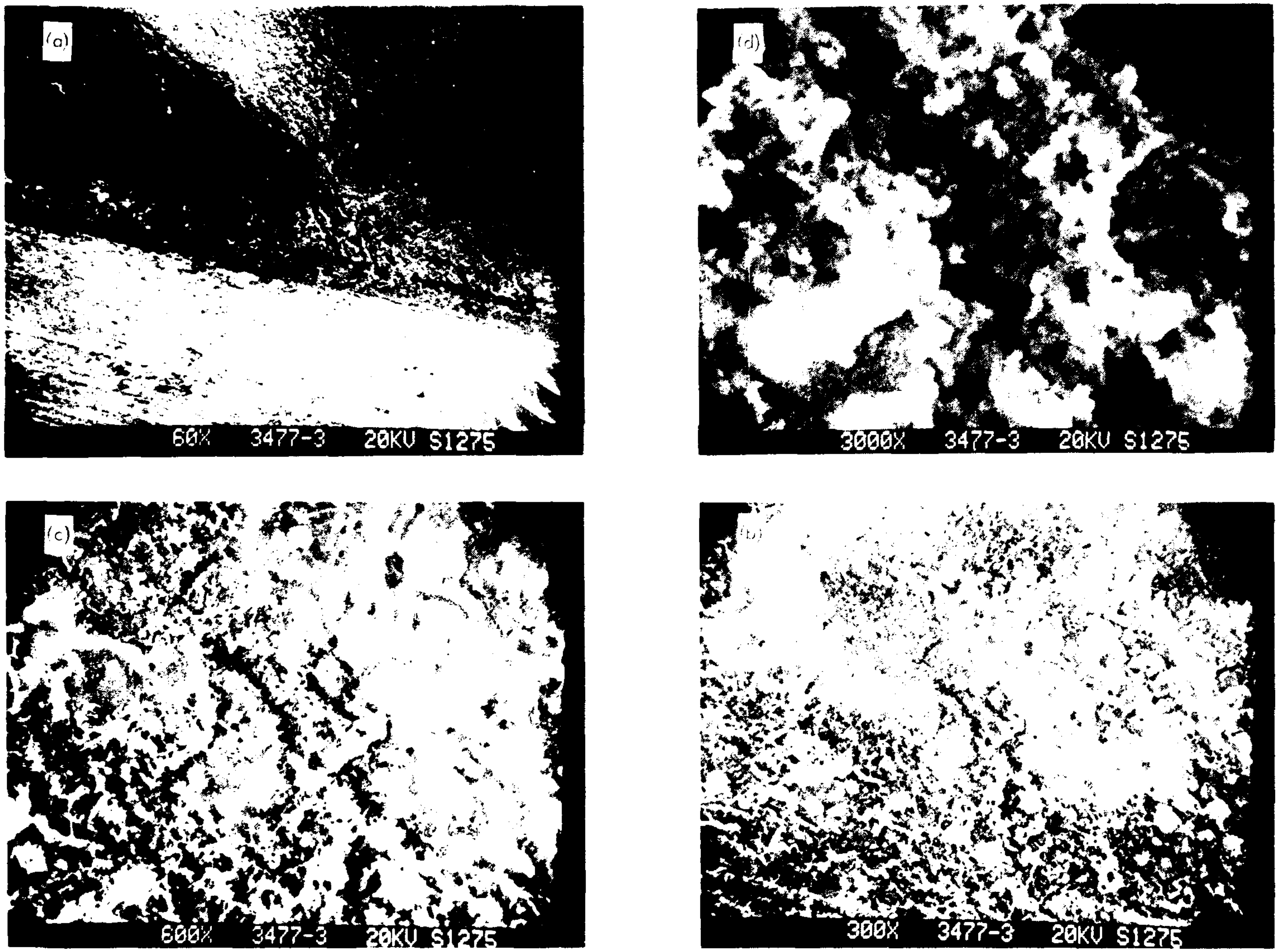

Figure D-12. Scanning Electron Micrography of Aluminum Alloy Type 6061 Specimen Exposed to Contaminated MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

APPENDIX C

Scanning Electron Micrographs of Corrosion-Resistant Steel Specimens:

1. Reference Specimen — Control
2. Propellant MMH — Baseline
3. Propellant MMH — Contaminated

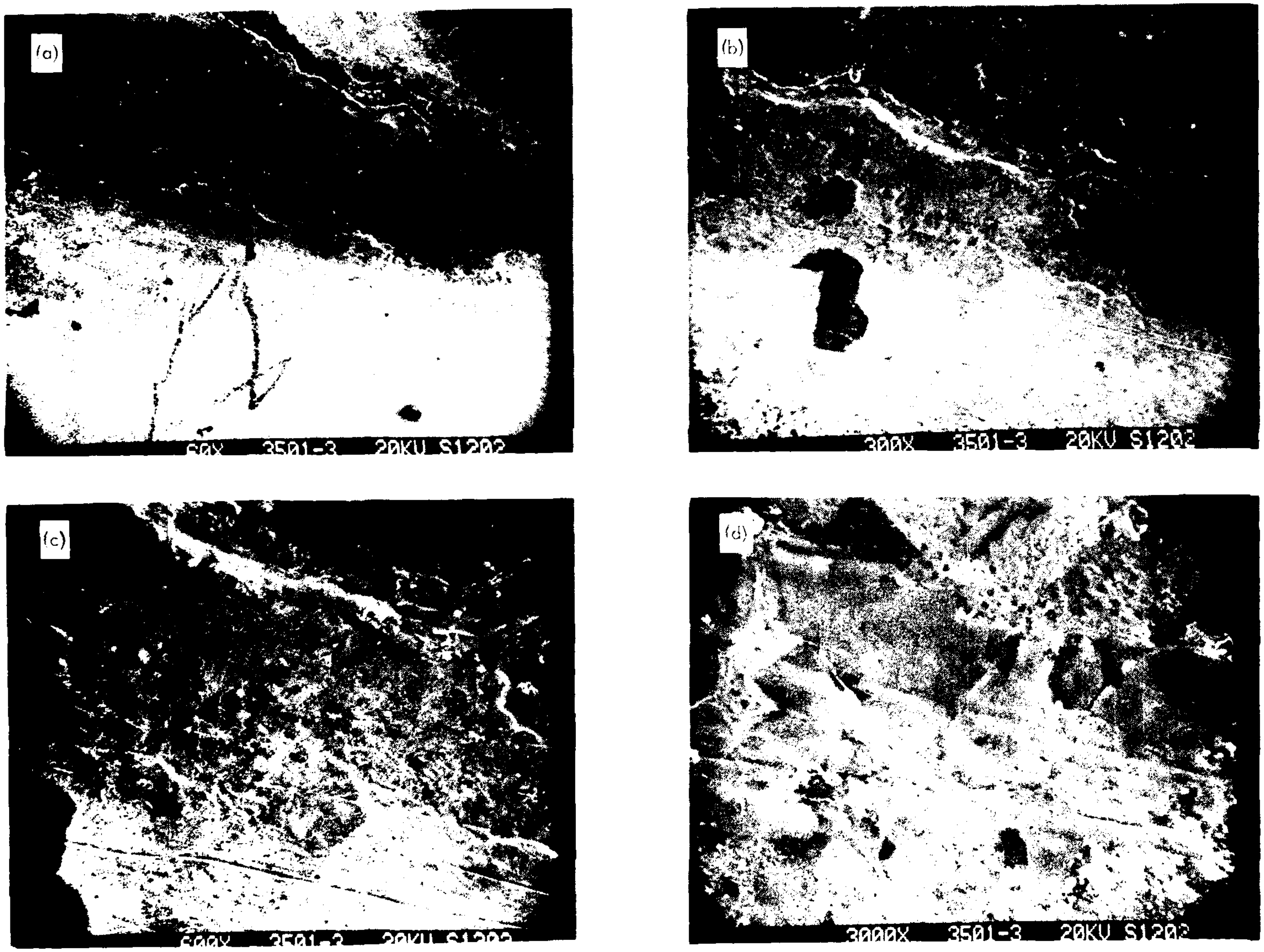

Figure C-1. Scanning Electron Micrography of CRES Alloy Type 316 — Reference Specimen: Control; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

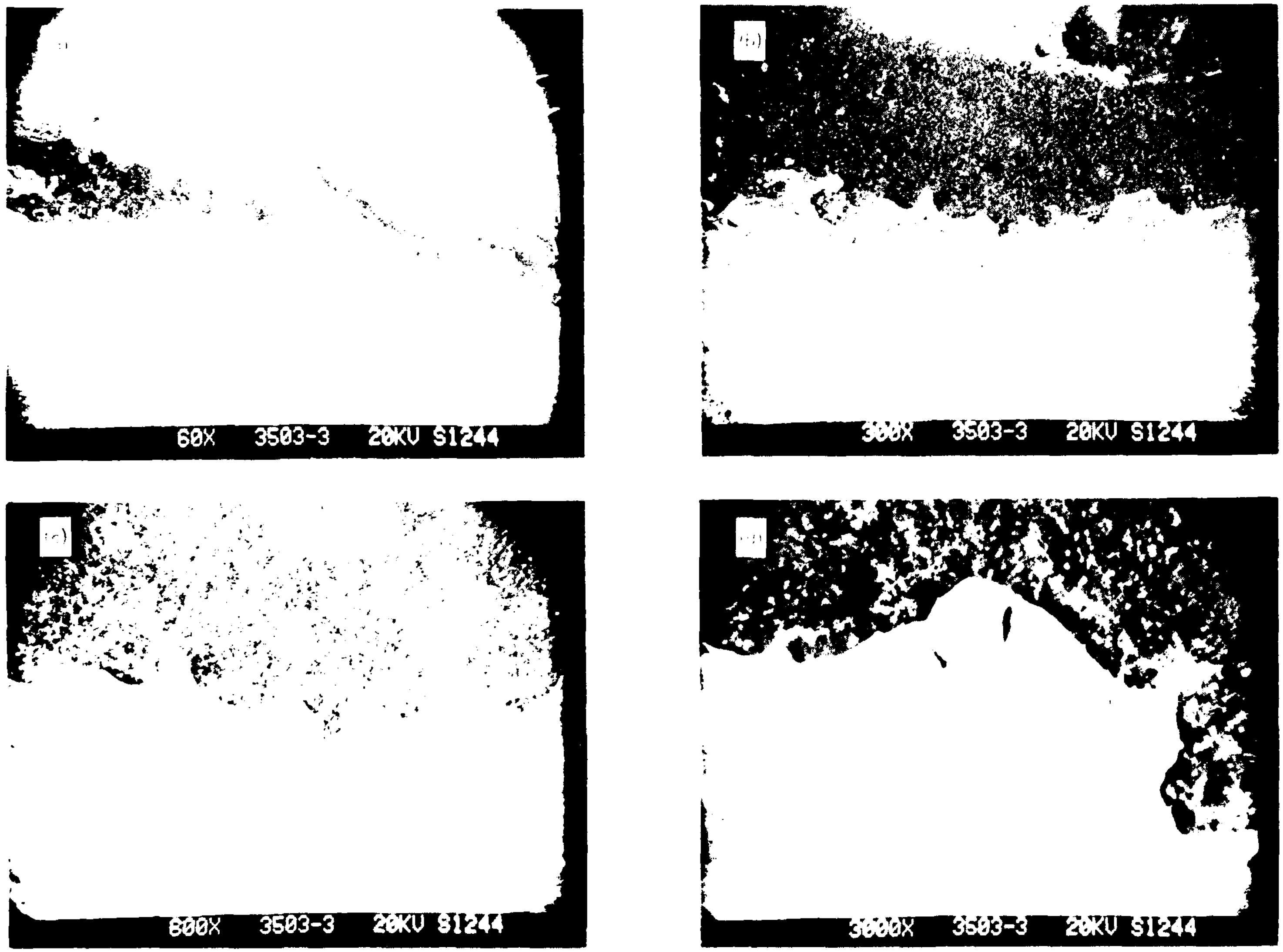

Figure C-2. Scanning Electron Micrography of CRES Alloy Type 316 — Specimen Exposed to Baseline MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

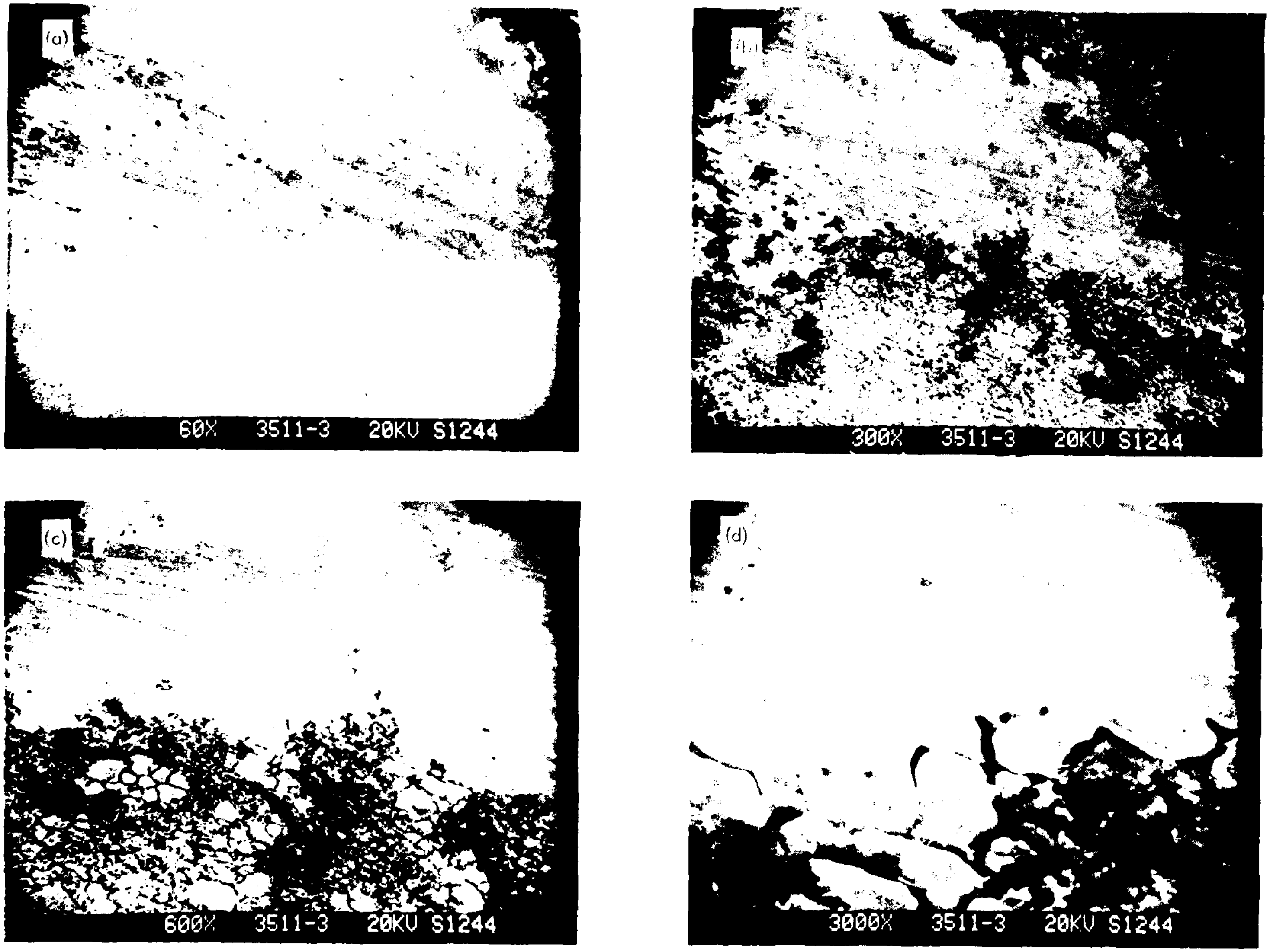

Figure C-3. Scanning Electron Micrography of CRES Alloy Type 316 — Specimen Exposed to Contaminated MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

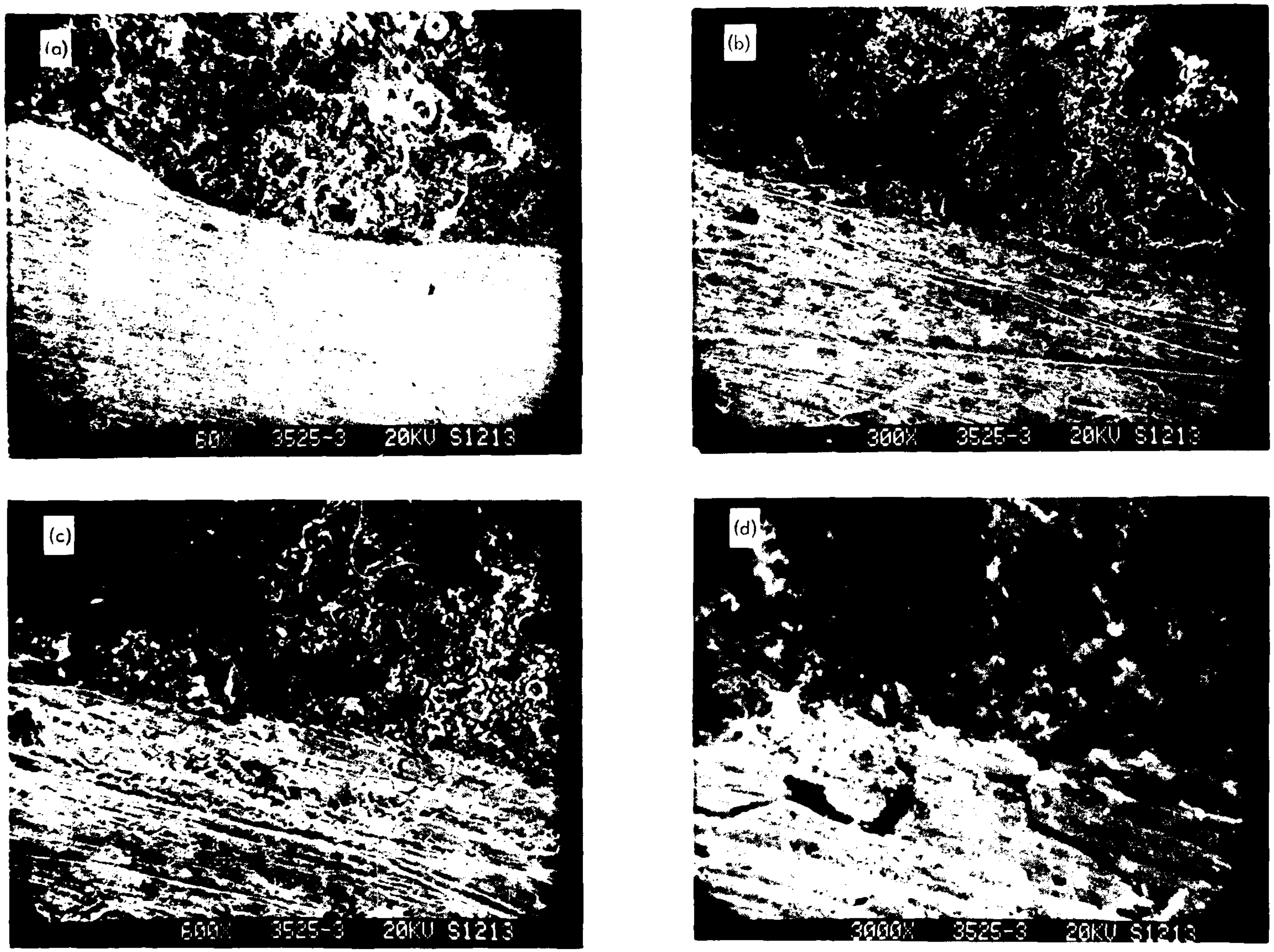

Figure C-4. Scanning Electron Micrography of CRES Alloy Type 316L — Reference Specimen: Control; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

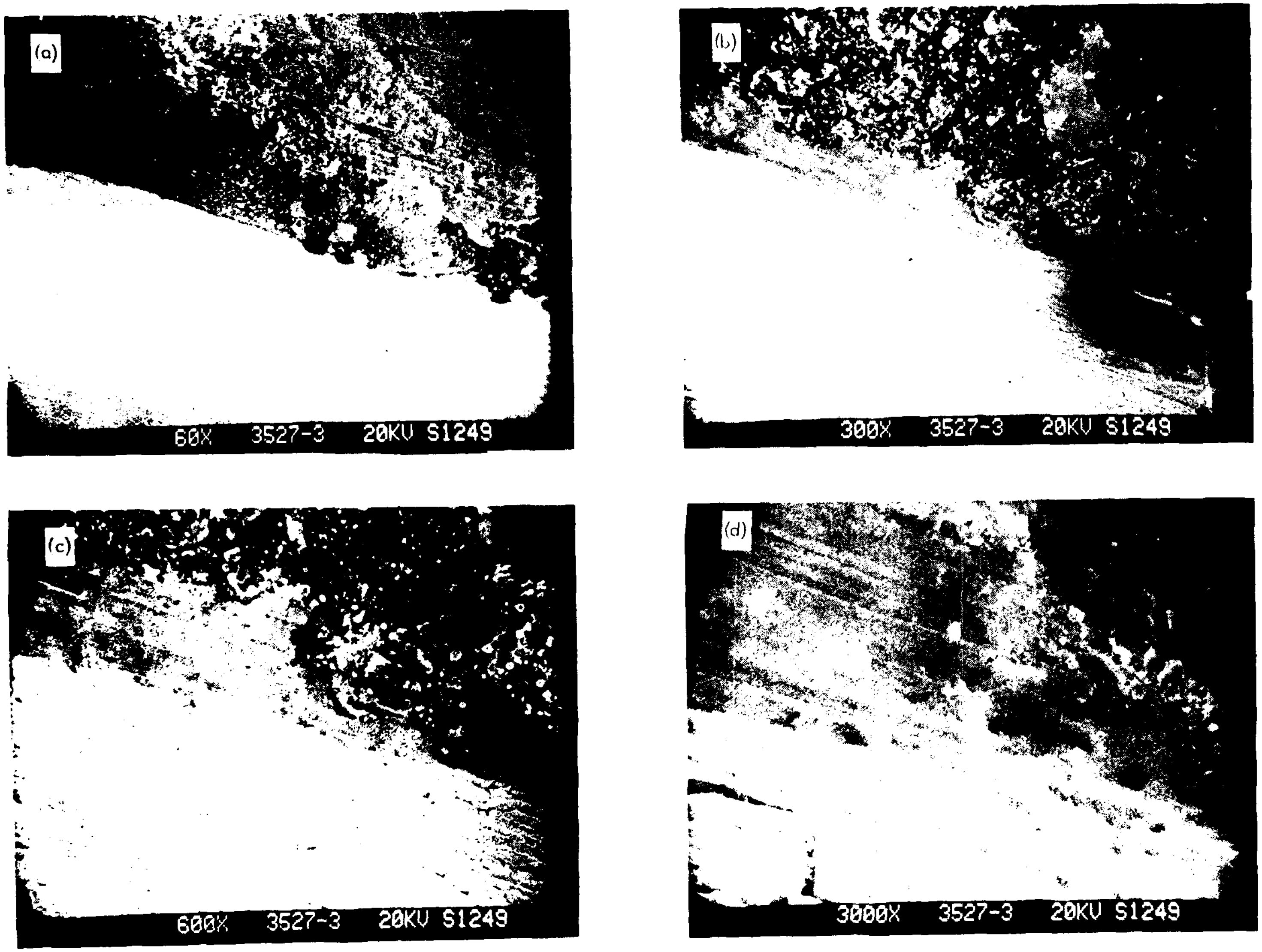

Figure C-5. Scanning Electron Micrography of CRES Alloy Type 316L — Specimen Exposed to Baseline MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

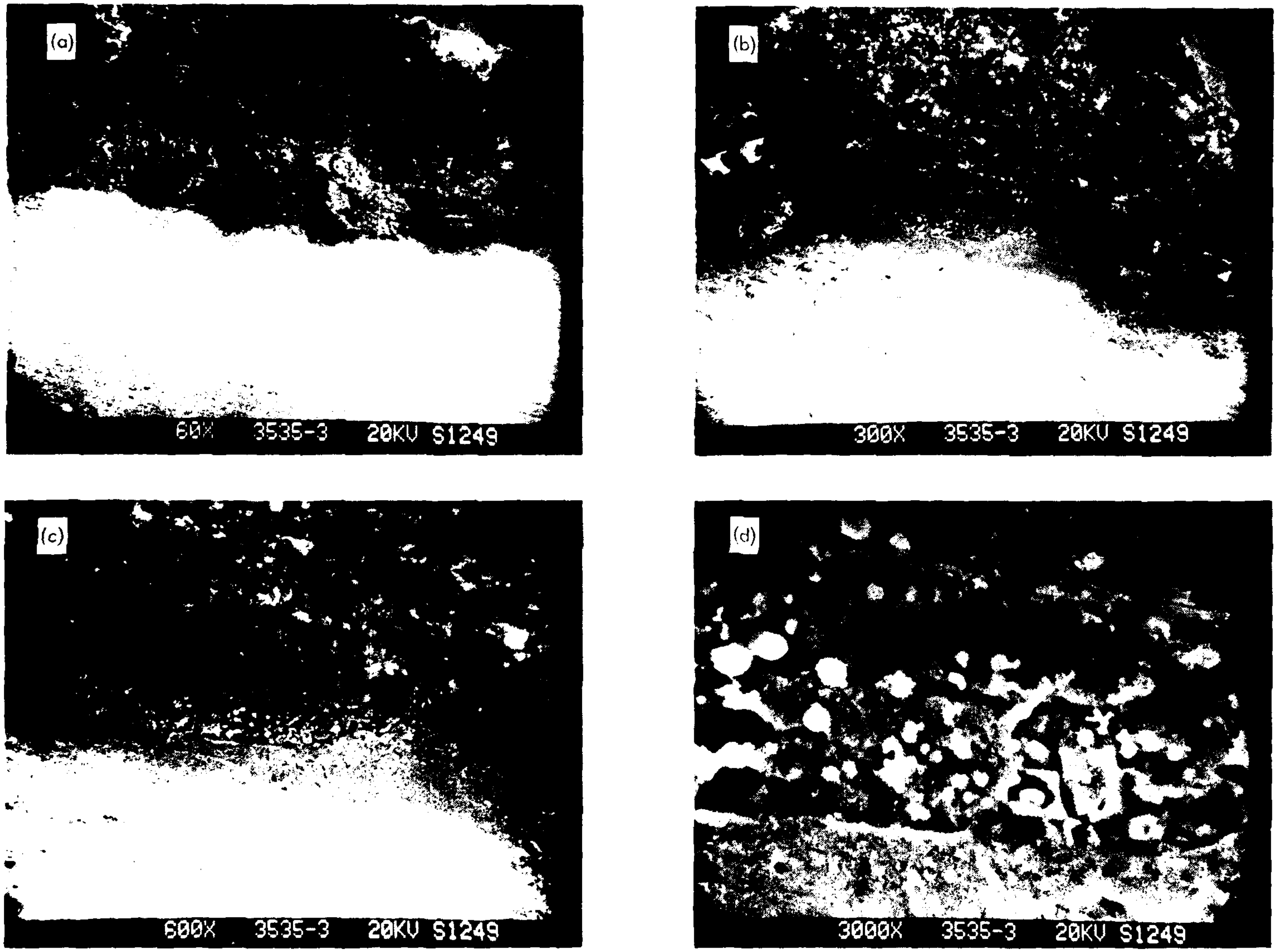

Figure C-6. Scanning Electron Micrography of CRES Alloy Type 316L — Specimen Exposed to Contaminated MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

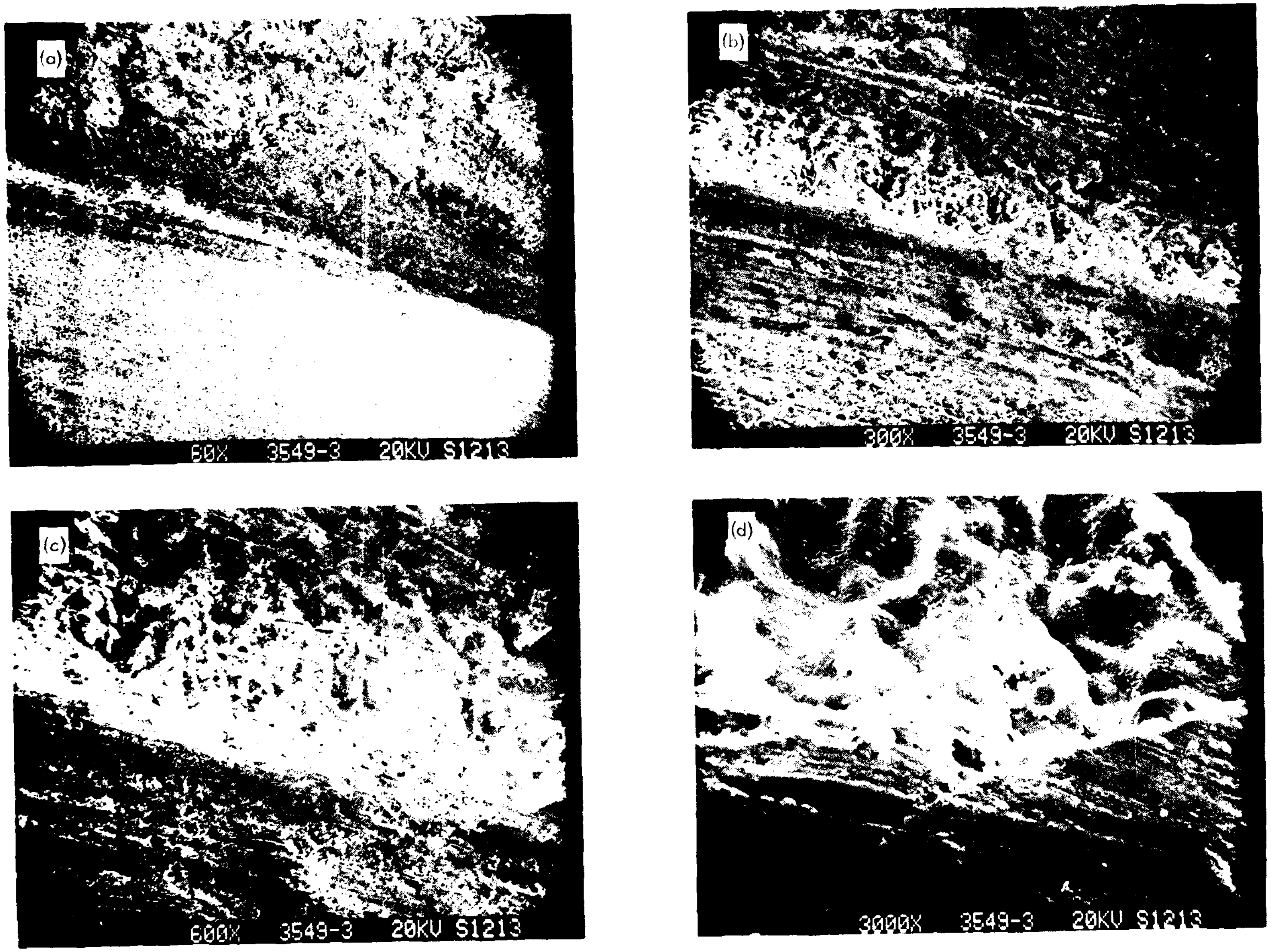

Figure C-7. Scanning Electron Micrography of CRES Alloy Type 321 — Reference Specimen: Control; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

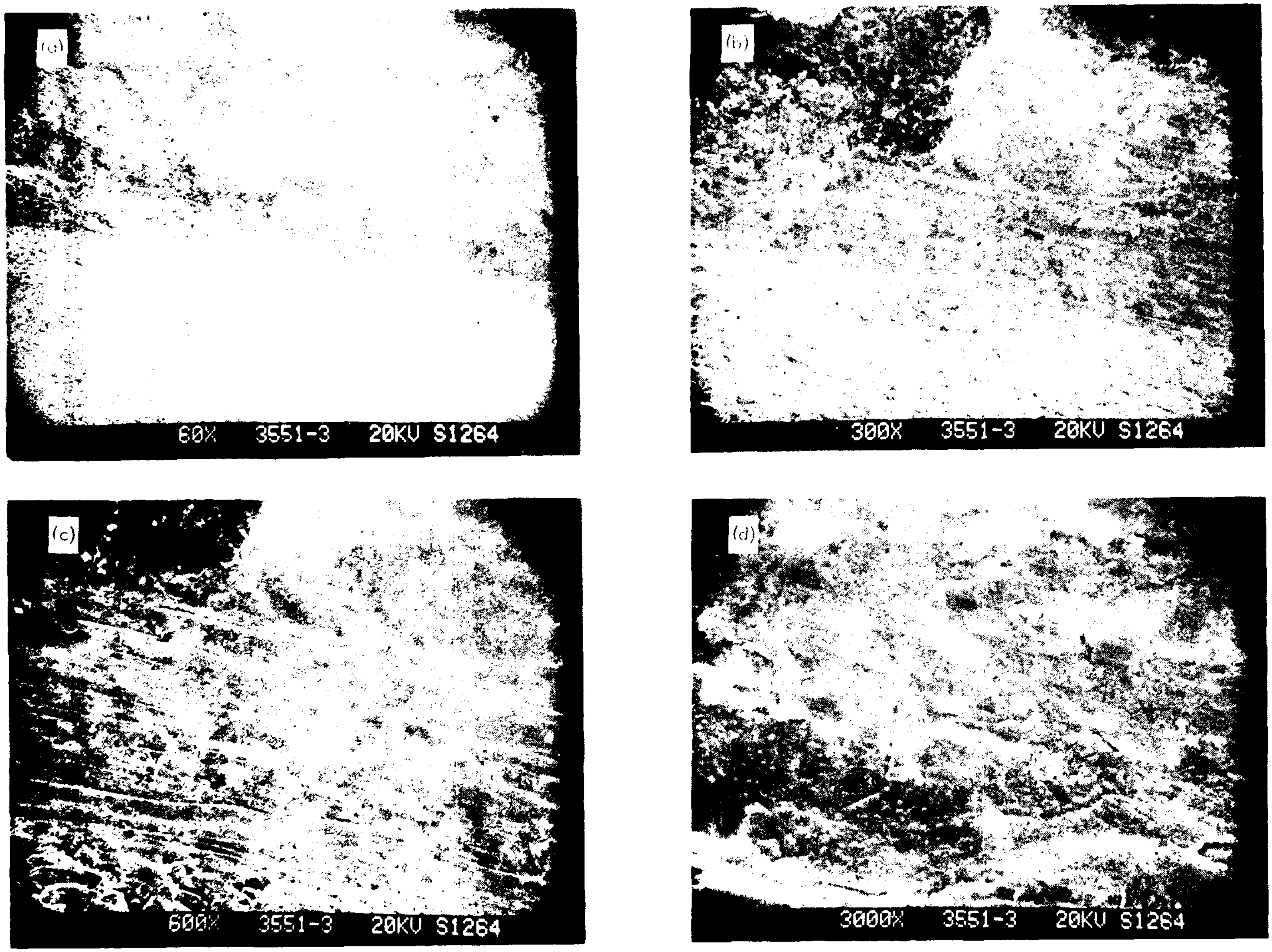

Figure C-8. Scanning Electron Micrography of CRES Alloy Type 321 — Specimen Exposed to Baseline MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

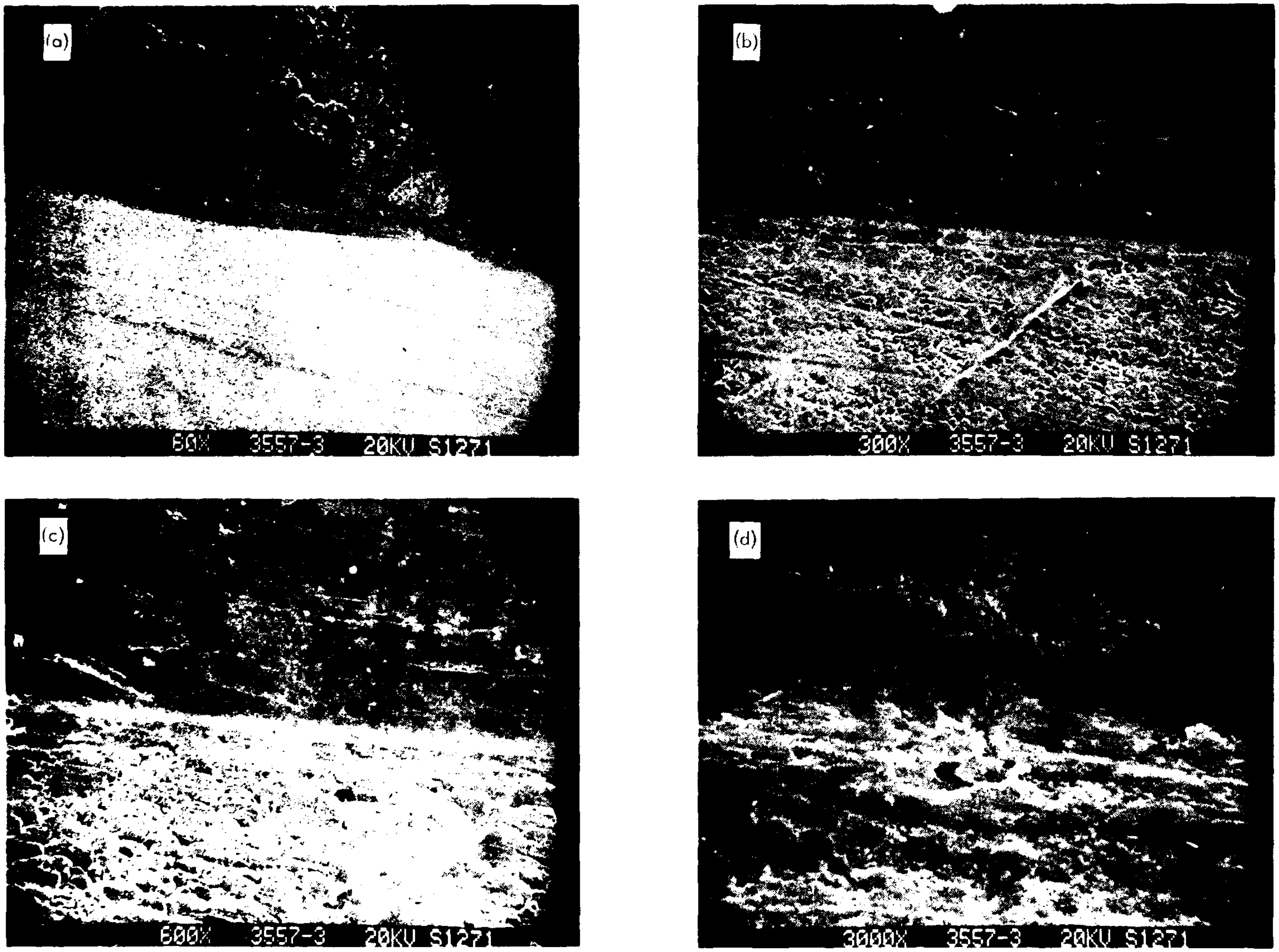

Figure C-9. Scanning Electron Micrography of CRES Alloy Type 321 — Specimen Exposed to Contaminated MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

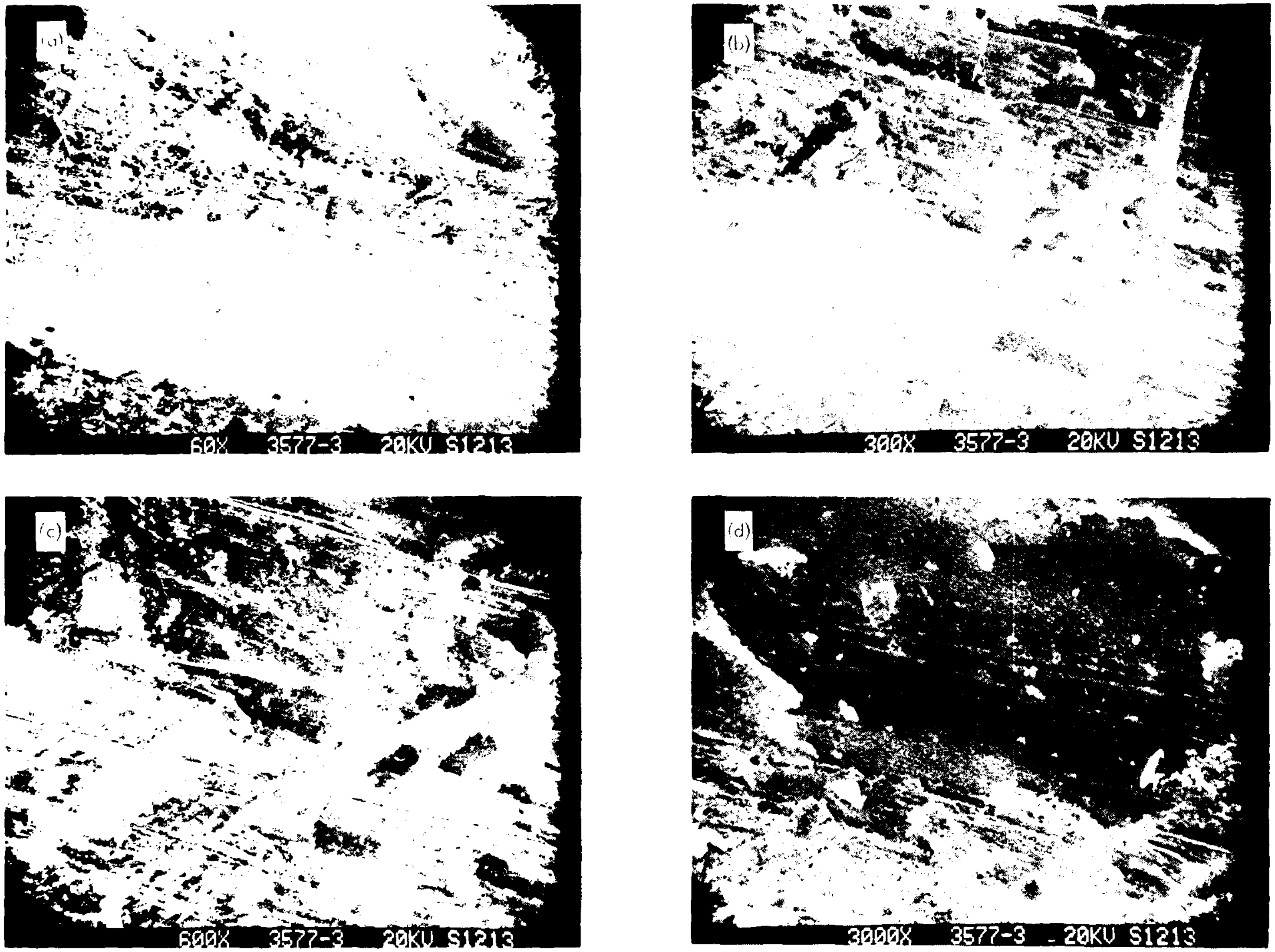

Figure C-10. Scanning Electron Micrography of CRES Alloy Type 430 — Reference Specimen: Control; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

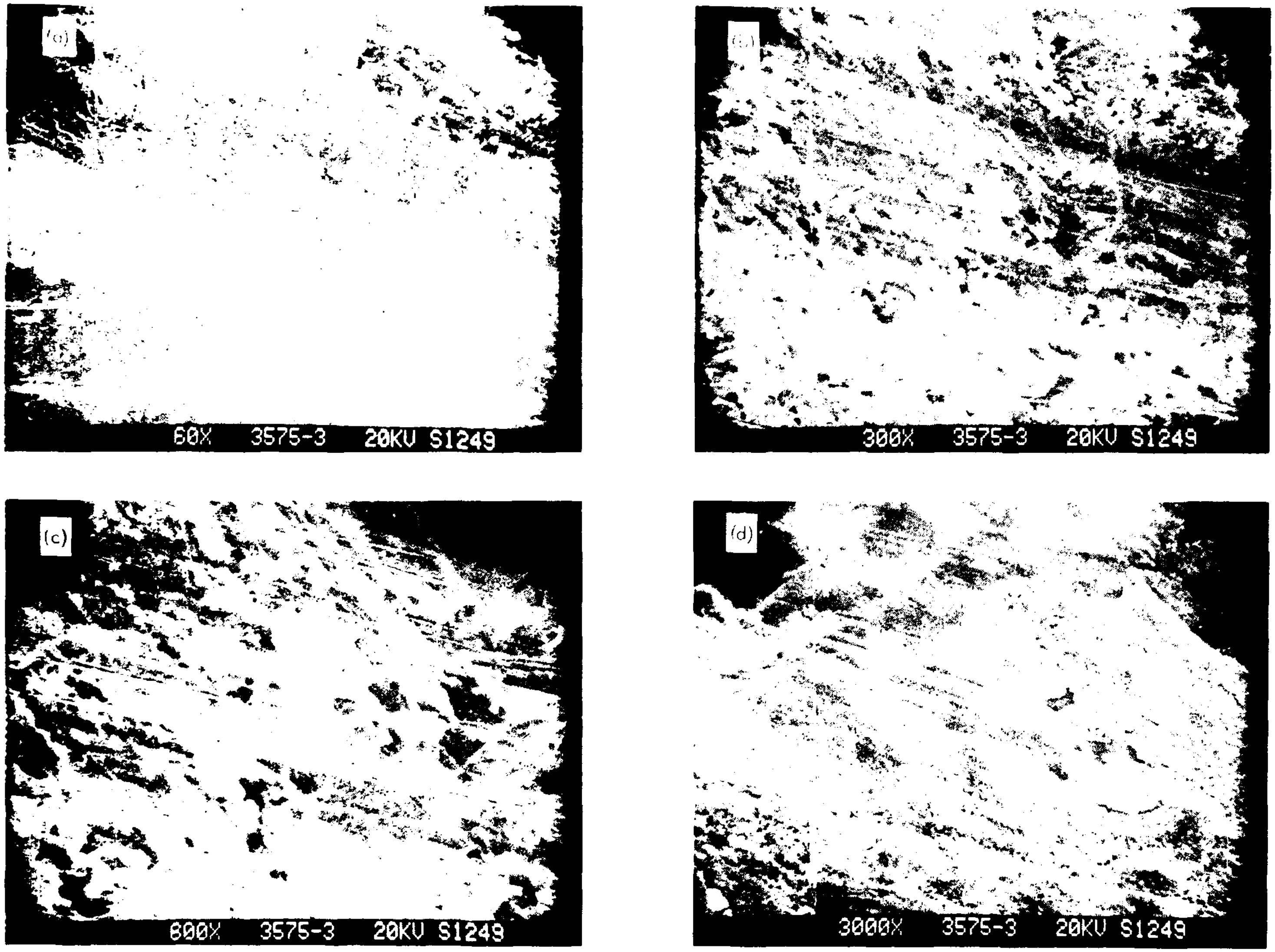

Figure C-11. Scanning Electron Micrography of CRES Alloy Type 430 — Specimen Exposed to Baseline MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X

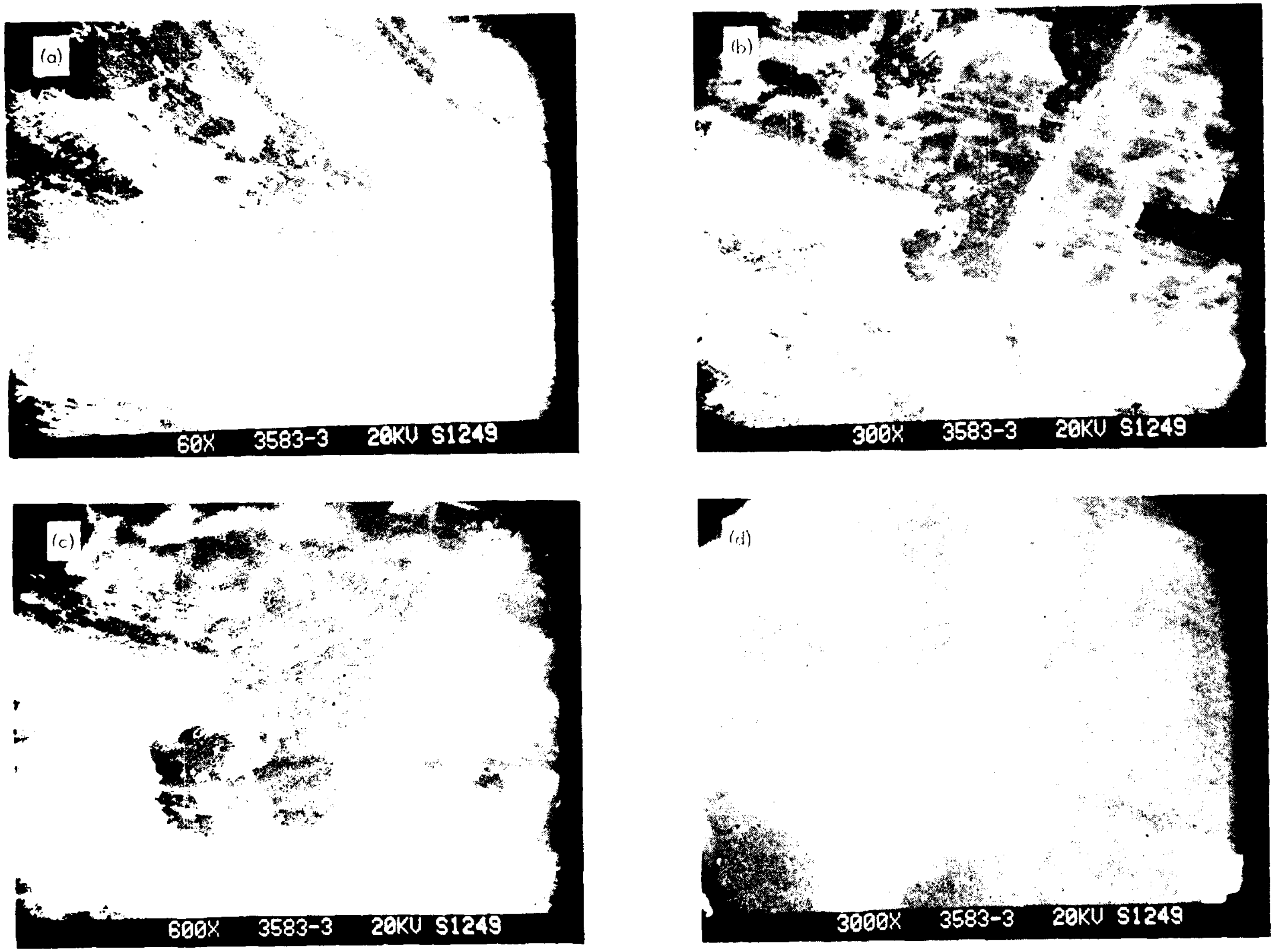

Figure C-12. Scanning Electron Micrography of CRES Alloy Type 430 — Specimen Exposed to Contaminated MMH; (a) 60X, (b) 300X, (c) 600X, (d) 3000X